THE
A.C. COMMUTATOR MOTOR

BY

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TO

MY WIFE

AUTHOR'S PREFACE

THE gradual standardisation of A.C. networks makes the use of A.C. motors essential in the greater number of industrial applications. On the other hand, the increasing demand for efficient speed regulation and a growing necessity for a high power-factor has led to the use of converting apparatus and D.C. motors, an expensive and inefficient process.

There is, for some reason which is difficult to appreciate, a strong prejudice against the A.C. commutator motor which affords an almost perfect solution to the problem, not perhaps so much by itself as when combined with the more usual induction motor. It is the object of this book to attempt to break down any such prejudice and show that the future lies with such combinations as will be described.

For convenience and clarity the book is divided broadly into two main parts: the first dealing with the analytical side, the second with the practical application of the motors.

The author particularly wishes to acknowledge his indebtedness to M. Marius Latour, whose pupil he had the honour to be at the Ecole Superieure d'Electricitée, Paris. Much of the analytical work in the first part of the book is based on M. Marius Latour's lectures.

A book of this kind could not have been written without the co-operation of a number of firms, for whose help the author begs to express his thanks. But he is more especially grateful to BRITISH BROWN-BOVERI, LIMITED, and the COMPAGNIE ELECTRO-MEÇANIQUE, PARIS, for their very valuable assistance. The remarkable work carried out by the FORGES ET ATELIERS DE CONSTRUCTIONS ELECTRIQUES DE JEUMONT (NORD) in connection with the A.C. commutator motor, and their willingness to afford the author every possible help, have enabled him greatly to increase both the analytical and practical chapters, and to include a number of actual test curves which he hopes will prove of interest to readers.

The author also wishes to extend his best thanks to the editor of *The Power Engineer* for permission to use the subject-matter and blocks of a series of articles contributed to that paper, and to the editors of *Colliery Engineering* and *The Railway Engineer* for permission to use blocks and information from their columns.

C. W. OLLIVER.

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CHAPTER I.

INTRODUCTION.

In spite of the possible advantages of high-voltage direct-current transmission systems and the vistas opened out by the transverter, the alternating current system of electric power production and transmission is undoubtedly the more popular at the present day. The choice is due to the ease of generating, transmitting, and distributing A.C. power, and also to the simplicity and robustness of the induction motor.

The induction motor, however, is essentially a constant speed machine, and as such its scope is limited. Wherever speed variation is necessary, the qualities of the induction motor are insufficient to offset the very uneconomical running conditions entailed by speed regulation.

The only solution to the problem of efficient and accurate speed control has been the installation of D.C. motors and conversion apparatus, or the use of such devices as the Ward-Leonard set.

A far simpler and more efficient solution, the use of A.C. commutator motors either alone or in combination with induction motors, has not yet found favour in this country.

It is the author's contention, backed by the results of continental practice, that this is due, not to inherent defects of the A.C. commutator motor, but to a lack of understanding of its properties and potentialities, and an unfounded prejudice, mainly with regard to commutation.

The phenomena of commutation are now much better understood, and it can be confidently stated that any difficulties of this kind have been entirely overcome. The commutator motor of the present day is as robust and free from trouble as the D.C. motor, and far more flexible.

Generally speaking, the stator of these motors is similar to that of an ordinary induction motor, and the armature resembles that of a direct-current motor, the commutator usually having larger dimensions than that of a direct-current motor of the same rating. The commutator motor is applicable to a variety of purposes, and there is practically no limit to the characteristics which may be obtained by the use of one or other of its many forms. The ease and efficiency of speed control, which may be obtained by merely shifting the brushes, is an added advantage, but the greatest of all is perhaps the very beneficial effect upon the power factor where such motors are installed.

A great amount of attention is now being given to the question of poor power factor, and this suggests that tariffs such as are commonly used to-day are unsuitable in present circumstances: The wattless component involves the supply undertaking in extra running costs, despite its having no energy content, and interferes very seriously with voltage regulation. Moreover, experience shows that without constant endeavour to effect an improvement, the power factor of a system is apt to grow steadily worse as more and more small users are connected up.

But it is a curious fact that although every type of apparatus such as rotary converters, static condensers, auto-synchronous motors, etc., have been installed for the purpose of raising the power factor, the A.C. commutator motor and its combinations, which afford a simple and efficient solution of the problem, have never been properly developed in this country.

Power companies have recently offered rebates on good power factors, and motors of this type afford the best means of getting a proper power factor with an A.C. supply.

It has been stated that the fundamental difficulty with these motors lies in the fact that the main alternating flux acts upon the short-circuited coils in the armature. The method of combating this is to introduce a neutralising flux, and as this involves the balancing of two large quantities, it would seem to be inherently difficult to obtain and maintain sufficient accuracy to ensure successful running.

It is hoped that the following chapters will dispel any such

misapprehensions, but it may be stated here that a large neutralising field is not necessary: a small interpole, i.e. a stator tooth excited to give correct phase and magnitude of flux density, is all that is needed, while exact counterbalancing is not essential.

The fear of the commutator is so deeply ingrained in the mind of the motor user that he will consider improving the power factor of the induction motor by means "not yet evolved" rather than examine the possibilities of a commutator motor from an unbiassed point of view. On the other hand, what means it is proposed to employ in order to modify what is a fundamental property of the induction motor, is a question left prudently alone: we do not envy anyone the job of tackling it.

It should be borne in mind that the author does not propose the A.C. commutator motor as a universal panacea suitable for every application. Both the induction motor and the synchronous motor have well-defined fields of utility. But trouble lies in that they are frequently misapplied and a commutator motor would give better and more efficient results.

One of the main reasons for the lack of interest that has been shown in the question of commutator motors is the absence of any recent comprehensive literature on the subject, whether in book form or in the form of articles in the technical press. To the best of the author's belief, the only recent contribution on the subject was a series of articles published by himself in *The Power Engineer*, much of which have been reproduced in the present volume.

The book has been divided into two distinct parts, in the hope that in this form it may appeal to a variety of readers.

The first part contains all the analytical treatment of the subject, which has been made as comprehensive as possible, while the second is devoted to a non-mathematical exposition of the principal applications of the commutator motor.

A short study of commutation is included as a preliminary chapter, after which the various forms of single-phase motors are studied analytically in some detail, leading naturally to a chapter on the polyphase motor, in which an attempt has been made to give a clear description in non-mathematical terms of

the principles underlying its theory. A further chapter is devoted to cascaded sets, and although the analytical theory of these is undoubtedly involved, the author has attempted to give a simple form of general equation applicable to such combinations.

In this chapter the question of power factor improvement and auto-compensated induction motors is thoroughly studied.

In the second part of the book, certain of the more important applications have been dealt with. In the first place, hoist, crane, and lift motors and their methods of control have been described.

The next chapter is devoted to a brief revue of single-phase traction, a subject altogether too vast to be exhaustively treated within the scope of this volume. In spite of the number of D.C. traction systems installed both in England and France, the single-phase system remains in favour where main-line electrification is concerned.

In this respect the commutator motor represents the only acceptable solution, and in no other field has it been so thoroughly developed. Typical locomotives of various types have been described, and an exposition of the reasons why various countries chose one or other of the systems has been given, in order that the reader may get an unbiassed view of the question.

The eighth chapter is devoted to one of the most important applications of the commutator motor in its combined form—the drive of rolling mills. This form of drive has been considerably used on the Continent with great and increasing success, and the possibilities of Kramer or Scherbius regulation are hardly realised at present.

Taken in conjunction with the fifth, this chapter should give a thorough analysis and practical study of the possibilities of cascaded sets, and, as far as the author has been able to ascertain, these facts have here been systematically set out in this form for the first time.

The final chapter deals with a variety of applications which have been grouped together in order to avoid undue repetition.

Whenever possible, actual test curves have been given for

the various motors mentioned or described, since this form of data is undoubtedly the most useful to students and prospective users.

Returning to the analytical part, it will be found that in every case the problem has been approached as far as possible from a number of different points of view, and that three main points have always been kept in mind and especially stressed, namely, power factor, efficiency, and commutation, these being the most important factors from the user's standpoint.

The analytical theory of these motors, and more particularly that of the cascaded sets, is unavoidably involved, but every effort has been made to simplify this by indicating the general lines to be followed, rather than attempting to press home intricate and unnecessary details.

Much of the theory of commutation and that of the single-phase commutator motor is based on the lectures of M. Marius Latour, whose work on these subjects is too well known to need any comment. It was owing to these lectures at the Ecole Superieure d'Electricité of Paris that the author first conceived the idea of writing a comprehensive treatise on this subject, the prejudice existing against these motors in England being an added incentive.

The author has in mind a paper read before a learned institution within recent years on the subject of power factor improvement, and the very lengthy discussions which followed, during the course of which *no mention* was made of the A.C commutator motor in any form whatsoever.

It is hoped that after reading the following pages, those interested in efficient power *utilisation*, which is as important, if not more so, than efficient power production, will be willing to give the A.C. commutator motor a fair trial.

CHAPTER II.

COMMUTATION IN DIRECT AND ALTERNATING CURRENT MACHINES.

ANY study of the commutator motor would be incomplete without an exposition of the problems of commutation. A clear understanding of the phenomena entailed should, in the author's opinion, prove of value, more particularly to designers, but also to users of commutator machines. There are few subjects which have led to so much discussion, to such a number of theories, as this problem, and its solution is due, mainly, to the investigation of M. Marius Latour, on the results of whose work the following theory is based.

Before entering into the theory proper, a few preliminary remarks are necessary in order to show up the problem in its true light, with its pitfalls and difficulties. It will be assumed throughout the following study that the armature is perfectly balanced, that there are no mechanical vibrations, that the commutator is true, and that the wear is equal for the copper and whatever insulation is used : in other words, that the mechanical side of the problem has been satisfactorily solved.

Let us now consider the surface of contact between a rotating copper slip-ring (representing a commutator, all the segments of which are connected together) and a carbon brush. Two fundamental facts have been established experimentally (Arnold), and may be stated as follows :—

Conditions for a Constant Flow of Current).—The apparent resistance ρ per unit contact surface is a function of—

(*a*) Brush pressure, and possibly peripheral speed.
(*b*) Surface temperature.
(*c*) Current density (ρ is inversely proportional to the density).
(*d*) Direction of current.

Conditions for a Rapidly Varying Density (in the case, for instance, of a fairly high frequency alternating current).—In this case the variations of ρ no longer follow variations in density, and ρ tends to retain a value such as would correspond to the density for a continuous current of intensity equal to the *effective* value of the alternating current considered. The quantity ρ, however, does follow the density variation to a certain extent, and must therefore be considered as a function both of the *effective* and *instantaneous* values of the current density.

Bearing these preliminary remarks in mind, it will be apparent that in any commutator machine the temperature, effective density, and even the pressure will vary along the arc of contact *ab* (Fig. 1).

The same will be true for the quantities of heat liberated at *a* and at *b*. It will be clear that the tempe[illegible]ments rise during their passage under the brush, so that the temperature will be higher at *a* than it is at *b*. Moreover, however perfectly the brush may be ground in to the commutator surface, it is probable that during rotation the pressure will vary along *ab*. The current density is, of course, an essentially variable quantity.

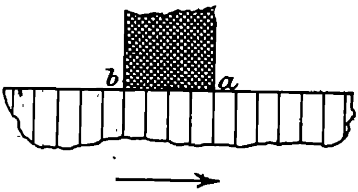

FIG. 1.—Diagram of brush and commutator.

It will be seen from the foregoing remarks that any hypothesis assuming a constant value for ρ at all points of the contact surface must necessarily be incorrect, since ρ is a function of pressure, temperature, effective density, and instantaneous density, all of which quantities are essentially variable. The order of magnitude of the error introduced by the assumption of a constant resistivity is not, however, as high as might be expected, and it is not suggested here that a study of the problem based on this assumption would be entirely erroneous or devoid of interest; but it remains a rough approximation, and does not correspond to reality.

Another difficult aspect of the problem is introduced by the consideration of the static capacity of the contact. The first mention of this factor is to be found in a paper by Henri

Poincaré as early as 1908. The existence and value of such a capacity can be experimentally verified by measuring the difference of phase between an alternating current flowing through the contact and the pressure drop across the contact. If v represents the peripheral speed of the commutator and d the width of a segment, $\frac{v}{d}$ will represent commutation frequency, and will be of the order of 1000 to 5000 cycles, and the frequency used for measuring the capacity should be within these limits.

In actual fact, the contact capacity may often be neglected, the more so because there are other capacities to be considered of a higher order of magnitude, such as the capacity of the short-circuited coil under commutation, or the capacity from segment to segment.

It is proposed to divide the study of commutation into two parts. The first will deal with the case when the armature is neither feeding any current to, nor receiving any current from, an exterior circuit, but where, for some reason such as incorrect brush-setting, or a variable field, caused perhaps by an alternating current, electromotive forces are generated in the armature section short-circuited by the brush. The second will deal with the case when the armature is generating or receiving current, that is, under normal operating conditions, and it will be seen that the solution of the second problem depends on a clear understanding of the first.

PART I.

Two cases will be considered. In the first it will be assumed that the two brushes are not connected to one another. In the second, it will be assumed that they are connected together, and in this case, consideration of the armature output will be avoided by assuming that it is counteracted (by the opposition of an exterior E.M.F., for instance).

Case I. The Brushes are not Connected Together.—We will assume that the width of the brush is equal to that of a segment, and that the number of segments is divisible by the number of poles, the winding being of the drum type. If the brushes are

exactly in opposition, there will be two armature sections short-circuited. Let L be the self-induction coefficient of each section S and S′ (Fig. 2), and M the coefficient of mutual induction.

Let e be the variable short-circuit E.M.F., r_1 and r_2 the variable contact resistances between the brush and the segments 1 and 2, r the constant resistance of the short-circuited coil. We can write the equation for the short-circuit current i—

$$e - (\mathrm{L} + \mathrm{M})\frac{di}{dt} - i(r_1 + r_2 + r) = 0 \quad . \quad . \quad (1)$$

We may represent e and i as curves by plotting them in function of time between the values 0 and T, at which the short-circuit is made and broken. For any given curve of e such as figure 3 will correspond a curve for i such as figure 3′.

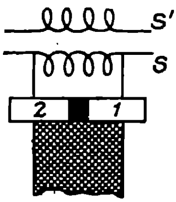

FIG. 2.—Diagrammatic winding, segments, and brush.

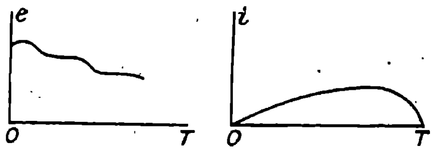

FIG. 3. FIG. 3′.
Voltage and current curves in short-circuited coil.

It is practically impossible, from equation (1), to deduce the value of i from the value of e. But the process may be reversed, and the curve for e deduced from the curve for i, because, if i and $\frac{di}{dt}$ are given at any instant t, we know all the factors in equation (1). The variable resistances r_1 and r_2 are known, since the effective and instantaneous densities along the arc of contact depend on the value of i. Let us consider only such i curves in which when $t = \mathrm{T}$, $i = 0$, and $\frac{di}{dt}$ is a finite quantity. Let Z represent the axial width of the brush, which will be a variable quantity, since the brush will never lie rigorously rectangular, and let Z_a be the axial depth at a, and v the peripheral speed; then, at the time $(\mathrm{T} - dt)$ the contact surface between the brush and segment 1 will be

$$\mathrm{Z}_a v dt,$$

the value of the current will be

$$0 - \frac{di}{dt}dt$$

and the current density along a at the time T will be

$$\delta_{a,\,T} = -\frac{1}{Z_a v}\left(\frac{di}{dt}\right)_{t=T} \quad . \quad . \quad . \quad (2)$$

the value i of the current itself being zero at that instant.

Let us consider the value $\rho_{a,\,T}$ of the resistivity at a at the time T. Equation (1) now becomes

$$e_{t=T} = \left[(L + M) - \frac{\rho_{a,\,T}}{Z_a v}\right]\left[\frac{di}{dt}\right]_{t=T} \quad . \quad . \quad (3)$$

From this expression it will be seen at once that if

$$(L + M) > \frac{\rho_{a,\,T}}{Z_a v},$$

then $e_{t=T}$ will be positive when $\left(\frac{di}{dt}\right)_{t=T}$ is positive, and negative when $\left(\frac{di}{dt}\right)_{t=T}$ is negative. If, on the other hand,

$$(L + M) < \frac{\rho_{a,\,T}}{Z_a v},$$

then $e_{t=T}$ and $\left(\frac{di}{dt}\right)_{t=T}$ will be of opposite sign.

At the time $t = 0$, e and $\frac{di}{dt}$ will have the same sign.

Let $\rho_{b,\,0}$ represent the value of the resistivity ρ along b at the time $t = 0$, and Z_b the depth of the brush along b. Then, by a similar process, we will get

$$e_{t=0} = \left[(L + M) + \frac{\rho_{b,\,0}}{Z_b v}\right]\left(\frac{di}{dt}\right)_{t=0}.$$

If now $(L + M) \geq \frac{\rho_{a,\,T}}{Z_a v}$ it can be shown that all i curves for which $i = 0$ and $\frac{di}{dt}$ is a finite quantity when $t = T$ will give e curves that will intersect the time abscissa, and for

$(L + M) = \frac{\rho_{a,\,T}}{Z_a v}$ all e curves will intersect the time abscissa at the point $t = T$. This may be demonstrated as follows:—

All conceivable i curves fall under three categories. They lie either entirely above the time abscissa, or below it, or partly on one side and partly on the other (Figs. 4, 5, 6, and 4′, 5′, 6′).

In the first two cases, it will be immediately apparent that $e_{t=0}$ and $e_{t=T}$ will have opposite signs, and the corresponding e curves are therefore of the form shown in Figs. 4′ and 5′. In the third case, there is an instant between $t = 0$ and $t = T$

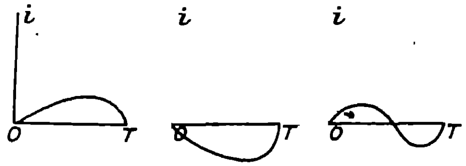

FIG. 4. FIG. 5. FIG. 6.

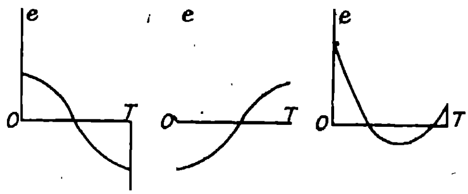

FIG. 4′. FIG. 5′. FIG. 6′.
Short-circuited coil, current, and voltage curves.

where $i = 0$ and $\frac{di}{dt}$ is of opposite sign to $\left(\frac{di}{dt}\right)_{t=0}$. At that instant e will be of opposite sign to $e_{t=0}$ and hence the e curve will be of the form shown in Fig. 6′. When $(L + M) = \frac{\rho_{a,\,T}}{Z_a v}$, we see from equation (3) that $e_{t=T} = 0$ at all times.

From this it will be seen that, with $(L + M) \geq \frac{\rho_{a,\,T}}{Z_a v}$ and a constantly positive, or constantly negative value of e between $t = 0$ and $t = T$, the density $\delta_{a,\,T}$ is certainly infinite. This will be more clearly understood if we consider that all curves of e for which, when $t = T$, $i = 0$, and $\frac{di}{dt}$ is finite, admit of

both positive and negative values of e. An e curve that admits only positive, or only negative values of e can only exist if $i \neq 0$ or if $\frac{di}{dt} = \infty$.

In either case, whether $i_{t-T} \neq 0$ or $\frac{di}{dt} = \infty$, it is obvious that $\delta_{a, T}$ will be infinite. This result may be directly deduced from equation (2).

Summing up the foregoing results, we find that when $(L + M) \geq \frac{\rho_{a, T}}{Z_a v}$, then—

(1) All forms of curves are admissible for i corresponding to appropriate curves for e, with the restriction that—

(2) Constantly positive or constantly negative values of e certainly entail a short-circuit current such that the density at the time $t = T$ will be infinite.

In other words, if the pressure drop due to the self and mutual inductance of the coils under commutation exceeds or equals that due to brush contact resistance, then the current density at the brush contact at the instant of breaking will rise to an infinite value. In practice the density, though it may rise to a considerable value, and thus cause bad sparking, can never actually become infinite.

It is, of course, impossible in practice to construct a brush and commutator in such a way that the brush breaks contact with the segment at the same instant along the whole of its depth. The brush will leave the segment obliquely and at the time T, $Z_a = 0$. Therefore, in practice, $(L + M)$ will always be smaller than $\frac{\rho_{a, T}}{Z_a v}$. Moreover, the variable contact capacity, small though it may be, will always exclude the possibility of an infinite density, even if the brush and segment edges were perfectly parallel. There is a further consideration that excludes such a possibility. If C is the capacity from one segment to another, q_2 the charge, and q_1 the quantity of electricity passing between the brush and segment 1, then we have the two equations

$$(L + M)\frac{d^2q_1}{dt^2} + (L + M)\frac{d^2q_2}{dt^2} + \frac{dq_1}{dt}(r + r_1 + r_2) = e,$$

and

$$\frac{dq_1}{dt}(r_1 + r_2) = \frac{q_2}{c}.$$

$\frac{dq_1}{dt} r_1$ represents the pressure drop between the brush and segment 1. It will be seen that the hypothesis of an infinite density would mean $q_1 = \infty$ and therefore $i = \frac{d(q_1 + q_2)}{dt} = \infty$, which is obviously impossible.

Let us now consider the case where $(\mathrm{L} + \mathrm{M}) < \frac{\rho_{a,\,\mathrm{T}}}{Z_a v}$. In this case, whatever form the variation of e may take, it may be shown that when $t = \mathrm{T}$, then $i = 0$, and $\frac{di}{dt}$ is finite, and that the density $\delta_{a,\,\mathrm{T}}$ is given by equations (2) and (3). The demonstration is easy if the brush is assumed to be perfectly rectangular, and ρ is taken as a constant. It will be equally easy to solve the more general problem if we consider Z_a and $\rho_{a,\,\mathrm{T}}$ as relating to a finite portion of the brush in the neighbourhood of a, and a definite period of time, both of which quantities may be chosen infinitely small.

In the above discussion we have assumed that the armature coils S and S′, short-circuited by brushes of opposite polarity, carried equal currents i. But in actual practice the short-circuits in these two coils will be made and broken at different times. To state the problem in its most general form, we must consider the fact that the brushes overlap unto other segments, and that besides the short-circuited coil S, there may be $(p - 1)$ other short-circuited circuits, among which we may have damping windings, or any special compensating windings or circuits of any kind.

These p circuits will of course give us p equations. For convenience, we will adopt the following notations. M_n^m will represent the mutual induction coefficient between circuit m and circuit n. M_n^n will therefore represent the self-induction coefficient of circuit n, and M_1^1 the self-induction coefficient of the armature coil S (which was previously written L). Let i_1, i_2, i_3 . . . i_p be the currents in the various circuits, and $(e - ir)_1$, $(e - ir)_2$ . . . $(e - ir)_p$ the ohmic drop and electromotive forces in each circuit.

We can now write the p equations :—

$$M_1^1 \frac{di_1}{dt} + M_1^2 \frac{di_2}{dt} + \ldots + M_1^n \frac{di_n}{dt} + \ldots + M_1^p \frac{di_p}{dt} = (e - ir)_1$$
$$M_2^1 \frac{di_1}{dt} + M_2^2 \frac{di_2}{dt} + \ldots + M_2^n \frac{di_n}{dt} + \ldots + M_2^p \frac{di_p}{dt} = (e - ir)_2$$
$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$
$$M_n^1 \frac{di_1}{dt} + M_n^2 \frac{di_2}{dt} + \ldots + M_n^n \frac{di_n}{dt} + \ldots + M_n^p \frac{di_p}{dt} = (e - ir)_n$$
$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$
$$M_p^1 \frac{di_1}{dt} + M_p^2 \frac{di_2}{dt} + \ldots + M_p^n \frac{di_n}{dt} + \ldots + M_p^p \frac{di_p}{dt} = (e - ir)_p.$$

If Δ represents the determinant formed from the induction coefficients that multiply $\frac{di}{dt}$ in the p equations, and Δ_n^1 represents the minor determinant obtained by suppression of the first column and nth line in Δ, we get

$$\frac{di_1}{dt} = \frac{\Delta_1^1(e - ir)_1 - \Delta_2^1(e - ir)_2 + \ldots \pm \Delta_0^1(e - ir)_p}{\Delta},$$

and multiplying by $\frac{\Delta}{\Delta_1^1}$.

$$\frac{\Delta}{\Delta_1^1}\frac{di_1}{dt} = (e - ir)_1 - \frac{\Delta_2^1}{\Delta_1^1}(e - ir)_2 + \ldots \pm \frac{\Delta_p^1}{\Delta_1^1}(e - ir)_p.$$

If we assume finite values for i, i_1, etc., and for e we will get for i a general equation of the form

$$E - \frac{\Delta}{\Delta_1^1}\frac{di_1}{dt} - i_1(r + r_1 + r_2) + 0,$$

where E is the sum of all electromotive forces and variable ohmic voltage drops, all of which are assumed to be finite quantities.

It will be at once apparent that in this case (L + M) has been replaced by $\frac{\Delta}{\Delta_1^1}$, a quotient which is mathematically equivalent to an induction coefficient, and that the conclusions regarding the value of the current density will apply here as before.

It has been shown * that determinants of the above type are always positive and are different from zero.

Therefore Δ and Δ_1^1 are both positive, and their quotient is also positive. But $\frac{\Delta}{\Delta_1^1}$ will always be considerably smaller than (L + M). Let us, for example, consider the case when the coil S′ is short-circuited while the coil S has already broken its short-circuit, which corresponds to the simple case of two circuits. Instead of (L + M) we must now consider

$$\frac{\Delta}{\Delta_1^1} = \frac{\begin{vmatrix} L & M \\ M & L \end{vmatrix}}{L} = \frac{L^2 - M^2}{L}.$$

If we represent by l the self-induction loss coefficient, (L − M) of the coils S and S′, we see that whereas in
the coefficient (L + M) was
practice we are left with a
mately equal to $2l$. If we consider the case where t
more than two circuits, the ratio will be smaller still.

It will be readily understood from the above remarks that in practice, twice the loss coefficient between two successive armature coils will be a maximum, and this value will be very small compared to L. The lowest value will occur when the two coils are in different slots of the armature.

When we consider the case of an alternating current commutator machine, where there are more than two rows of brushes per pole (phase multiplication, for instance), it is possible that the number of brushes per pole should be such that, at any instant, there will be at least one armature coil short-circuited in each slot. In this case, $\frac{\Delta}{\Delta_1^1}$ is practically equal to zero. (See remarks on squirrel-cage commutation.)

It is interesting to imagine what the short-circuit current would be, in the case where the brush covers more than one segment, if there were no losses between successive sections.

We may express this by saying that each coil would *inherit*, so to speak, the short-circuit current of the preceding coil, and

* Marius Latour, "Sur quelques théoremes generaux relatifs á l'electrotechnique" (*Eclairage Electrique*, 6 Avril, 1907).

that the sum of the ampere-turns created by the short-circuit currents would remain constant. This sum would itself depend on the average value of the various electromotive forces e, and on the average resistance of all possible positions of a segment under the brush during the period T.

Finally, we can consider the case when the armature is infinitely sub-divided, and consequently $\frac{\Delta}{\Delta_1^1}$ is necessarily equal to zero ((L + M) being zero), and find the form of the short-circuit current, assuming losses between successive armature coils.

In this case the current will satisfy a differential equation of the form

$$Ai + \frac{d^3i}{dt^3} = B\frac{de}{dt},$$

when A and B are constants.

Assuming e constant, and writing $a = \sqrt[3]{A}$, we get by integration

$$i = C\epsilon^{-at} + C^1\epsilon^{\frac{at}{2}} \sin\left(\frac{a\sqrt{3}}{2}t + C''\right)$$

(ϵ represents the base of Naperian logarithms; C, C′, C″ integration constants).

If in this equation we neglect losses, A = 0, and the curve representing the current, for a constant electromotive force, would be a parabola.

Case II. The Brushes are Connected to One Another.— Although we have only considered the case where the brushes neither receive nor feed current from or to an exterior circuit, it should be noticed that the presence of a short-circuit current in the brushes is equivalent to an apparent pressure drop, g, in the brushes as far as an exterior circuit is concerned.

Let us for the moment assume that ρ is constant and that e is also constant during the period T. Then, if p_1 is the ohmic drop at any instant for the front edge of brush α, p_2 the ohmic drop at any given instant along the rear edge of brush β (see Fig. 7), it will be seen that the value of the ohmic drop under the brushes at any given instant will be $p_1 + p_2$. But, for reasons of symmetry, the drop p_2 at any instant under the rear

edge of brush β is equal to that under the rear edge of α. It follows that the value at any given instant of the ohmic drop under the brushes, g, is equal to the algebraical sum of the ohmic drops at the rear and front edges of any brush α.

The average value will clearly be the sum of the average values of p_1 and p_2.

This average value can be experimentally obtained by means of a very narrow auxiliary brush placed first in line with the front edge and then in line with the rear edge of the brush, the pressure drop between it and the body of the main brush being measured in each case.

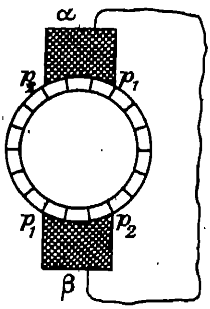

FIG. 7.—Diagram of commutator and brushes showing ohmic drops.

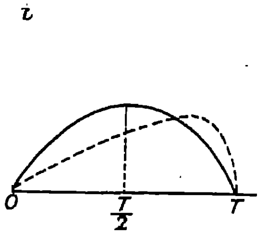

FIG. 8.—Effect of self-induction on current curve.

Let us now return to the case where the brush and segment are of equal width.

The values of p_1 and p_2 at any given instant will be

$$ir_1 \text{ and } -ir_2,$$

so that the value of g will be $i(r_1 - r_2)$ at any instant, and its average value will be

$$\frac{1}{T}\int_0^T i(r_1 - r_2)dt.$$

If the short-circuited coil had no self-induction, and since we have assumed ρ constant, the i curve would take the form of a parabolic arc (Fig. 8), and i would rise to a maximum for $t = \frac{T}{2}$ when the resistance $r_1 + r_2$ reaches a minimum.

But, on account of the presence of self-induction, the curre
i will rise to a maximum value at some time after $t = \frac{T}{2}$, a
the i curve will be of the form shown in dotted lines.

Let us examine the integral

$$\frac{1}{T}\int_0^T i(r_1 - r_2)dt$$

in the light of these remarks.

Taking two infinitely small elements of this integral cor
sponding to times t and $T - t$, with $t < \frac{T}{2}$, we see that at bo
these times $r_1 - r_2$ will have the same value, but will ha
changed in sign. A glance at the dotted curve will sho
however, that the value of i is greater for $T - t$ than it is fo
From this it will be obvious that the semi-integral

$$\int_{\frac{T}{2}}^T i(r_1 - r_2)dt,$$

will be greater than the semi-integral

$$\int_0^{\frac{T}{2}} i(r_1 - r_2)dt,$$

and that the total integral

$$g_{\text{average}} = \frac{1}{T}\int_0^T i(r_1 - r_2)dt$$

must therefore be always $\neq 0$, and its sign will depend on
direction of i, that is, on the sign of e. It will be seen t
g_{average} is positive for a lag and negative for a lead.

As soon, therefore, as the brushes are connected togeth
we find a variable current j, independent of the current i ir
and which tends to follow the fluctuations of $i(r_1 - r_2)$.
represents the current flowing through the resistances r_1 and
and L_{ex} the self-induction of the outer connection betw

brush α and brush β, including the armature, by R, the resistance of this circuit, then we may write

$$i(r_1 - r_2) = j\mathrm{R} - \mathrm{L}_{ex}\frac{dj}{dt}.$$

The current flowing through S becomes $(i + j)$, and the fundamental equation becomes

$$e - (\mathrm{L} + \mathrm{M})\left(\frac{di}{dt} + \frac{dj}{dt}\right) - (i + j)r - i(r_1 + r_2) = 0.$$

(It is assumed that there is no mutual induction between S and S′ on the one hand, and the remaining portion of the armature on the other.)

Substituting for $\frac{dj}{dt}$ we find that the coefficient of $\frac{di}{dt}$ will be

$$\frac{(\mathrm{L} + \mathrm{M})\mathrm{L}_{ex}}{(\mathrm{L} + \mathrm{M}) + \mathrm{L}_{ex}} = \frac{(\mathrm{L} + \mathrm{M})}{1 + \frac{(\mathrm{L} + \mathrm{M})}{\mathrm{L}_{ex}}}.$$

It is interesting to note here that the effect of the connection $\alpha\beta$ is merely to add one more circuit to the various p circuits considered earlier in this chapter. This will be made apparent by forming

$$\frac{\Delta}{\Delta_1^1} = \frac{\begin{vmatrix}(\mathrm{L} + \mathrm{M})(\mathrm{L} + \mathrm{M}) \\ (\mathrm{L} + \mathrm{M})(\mathrm{L} + \mathrm{M}) + \mathrm{L}_{ex}\end{vmatrix}}{(\mathrm{L} + \mathrm{M}) + \mathrm{L}_{ex}} = \frac{(\mathrm{L} + \mathrm{M})}{1 + \frac{(\mathrm{L} + \mathrm{M})}{\mathrm{L}_{ex}}}.$$

It is this term $\frac{(\mathrm{L} + \mathrm{M})}{1 + \frac{(\mathrm{L} + \mathrm{M})}{\mathrm{L}_{ex}}}$ that will tell us if $\delta_{a,\mathrm{T}}$ will be infinite or finite. If

$$\frac{(\mathrm{L} + \mathrm{M})}{1 + \frac{(\mathrm{L} + \mathrm{M})}{\mathrm{L}_{ex}}} > \frac{\rho_{a,\mathrm{T}}}{Z_a v},$$

then $\delta_{a,\mathrm{T}} = \infty$ and so also would we have $\left(\frac{dj}{dt}\right)_{t=\mathrm{T}} = \infty$.

Practically, $\frac{\mathrm{L} + \mathrm{M}}{\mathrm{L}_{ex}}$ is very small, and the fact of considering an exterior connection between the brushes does not change the conditions for which $\delta_{a,\mathrm{T}} = \infty$. It should be remembered, however, that the circuit $\alpha\beta$ is traversed by a variable current j

due to the ohmic drop, g, under the brushes, which is unchanged by the number of segments in simultaneous contact with the brush.

The value of g has been experimentally measured by Latour, and the fact verified that it is positive when the brushes are set in advance of the neutral line, and negative in the opposite case.

The results may be summed up by stating that a possibility arises of $\delta_{a,\tau}$ becoming infinite whenever $Zv\frac{\Delta}{\Delta_1^1}$ has a high value, and that the only guarantee which we have in practice that $\delta_{a,\tau}$ will not rise to infinity is due to the brush edges being oblique, and to the presence of capacity effects. But this is sufficient to ensure that $\delta_{a,\tau}$ will remain within reasonable limits so long as e does not become very large simultaneously with a high value of $Zv\frac{\Delta}{\Delta_1^1}$. In other words, the term on which the density at rupture depends will be

$$e \,.\, Zv \,.\, \frac{\Delta}{\Delta_1^1},$$

and this expression should not exceed a certain given value for a certain given brush. In this expression e may be taken more generally as the E.M.F. induced in the whole short-circuited portion of the armature between the extreme edges of the brush, and this will be a true expression in cases where the brush covers several segments simultaneously.

One may conclude from these statements that the quality of commutation will depend on each of the factors of the product $e \,.\, Zv \,.\, \frac{\Delta}{\Delta_1^1}$ being as small as possible.

Some remarks are here necessary concerning the effect of *resistant connections* between segments and armature.

Let β represent the ratio of the total resistance of the segment-armature junctions to the resistance R_1 of the brush-commutator contact. (By the total resistance of the segment-armature junctions we mean the resistance of one junction r when the brush covers one segment, $\frac{r}{2}$ when the brush covers

two, etc.) Let e be the total E.M.F. in the short-circuited portion of the armature. We can write the expression for the heat released under the brush per second and per square centimetre as $\frac{e^2}{\rho}f(\beta)$.

In fact, the presence of resistant connections will reduce very considerably the quantity of heat generated in the contact, and as such they are beneficial as a limiting factor when e tends towards dangerous values.

PART II.

We will now study the problem in its more general form, that is, when the armature is receiving or generating a current I. We will first of all deal with the case of direct current.

It is well known that *perfect commutation* is obtained when the current density under the brush is uniform during the period of commutation, which corresponds also to a linear variation of the current.

To obtain this effect in practice, it becomes necessary to introduce into the short-circuited armature coil a certain reversing E.M.F. which we will call E_p. Under operating conditions, the E.M.F. considered, E, will never have the correct value E_p, and we will designate by e the difference $e = E - E_p$ (e, E, and E_p are, of course, variable from $t = 0$ to $t = T$). The whole problem, then, lies in the study of $E - E_p$, that is, in the study of E and E_p.

Study of E_p.—If we consider the case of a rectangular brush covering only one segment, it is easy to see that perfect commutation requires a linear variation of current, that is, the current in the armature coil under commutation will vary from $-\frac{I}{2}$ to $+\frac{I}{2}$ according to the mathematical law expressed by

$$i = I\frac{t}{T} - \frac{I}{2}.$$

If r represents the constant short-circuit resistance, then

$$E_p = \frac{(L + M)I}{T} + \left(I\frac{t}{T} - \frac{I}{2}\right)r.$$

If we neglect r, then we get

$$E_p = \frac{(L + M)I}{T}.$$

But in the most general case, we cannot assume that the brush is perfectly rectangular, which means that its depth z along ab is a variable quantity.

In this general case we will have

$$\frac{1}{T}\int_0^T E_p \epsilon^{\frac{r}{(L+M)}t} dt = \frac{(L + M)I}{T} \tfrac{1}{2}\left(1 \times \epsilon^{\frac{-rT}{L+M}}\right).$$

It may be deduced from the above equation that all E_p curves, plotted from O to T, each one corresponding to different shapes of brushes, will intersect each other in pairs. If, moreover, the ratio $\frac{rT}{L + M}$ is negligible, then

$$\frac{1}{T}\int_0^T E_p dt = \frac{(L + M)I}{T},$$

hence, in this case, the average value of E_p will be independent of the shape of the brushes.

By increasing the value of r (resistant connections), and by choosing an appropriate section for the brushes, E_p may be increased indefinitely.

If, on the other hand, our object is to obtain a minimum value for E_p, we find that the best we can do is to reduce E_p to a constant value equal to $0{\cdot}982 \ldots \frac{(L + M)I}{T}$, by making $\frac{rT}{(L + M)} = 0{\cdot}132 \ldots$ (this is found by varying r).

This shows that even by using appropriate resistant connections together with a correct brush section, we cannot appreciably decrease the value of E_p.

If the brush covers several segments, then, calling L the self-induction of the various portions of the armature winding that are short-circuited under each brush, and M the coefficient of mutual induction of the two portions under brushes of

opposite polarity, the value of the E.M.F. in each portion must still be, for perfect commutation,

$$E_p = \frac{(L + M)I}{T}.$$

Hence, sub-division of the armature cannot bring about a modification of the expression for E_p.

Let us consider the case of an armature winding, fitted with a commutator, and placed within an ordinary induction motor stator with evenly spaced slots.

Any current I flowing through the armature will create a flux, the average direction of which will be that diameter on which the current is fed to the armature. It can be conceived that this flux is stationary in space during the rotation of the armature, and that a certain E.M.F. is induced, on this account, in the short-circuited coils which are moving through the field.

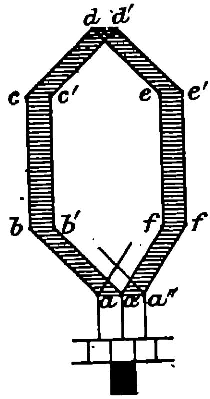

FIG. 9.—Diagrammatic adjacent armature coils.

If the brush width is equal to the width of a segment, a necessary condition for the stationary flux considered, it can be shown that the E.M.F. will be expressed by the term $\frac{(L + M)I}{T}$.

Let a, b, c, d, e, f, and a', b', c', d', e', f' (Fig. 9) represent two adjacent armature coils, which, for simplicity, we will assume to be formed of single turns. If ϕ_1 is the average value of the magnetic flux created within, $a, b, c, d, d', c', b', a'$ (situated on a cylindrical surface at a certain depth within the slots), and ΔS the surface $a, b, c, d, d', c', b', a'$, and T the time which a, b, c, d takes to move to the position a', b', c', d', then the E.M.F. induced in a, b, c, d will be

$$\frac{\phi_1 \Delta S}{T}.$$

If ϕ_2 represents the average value of the field within $defa'a''f'e'd'$, and assuming a positive direction opposite to that chosen for ϕ_1, the E.M.F. induced in $defa'$ will be

$$\frac{\phi_2 \Delta S}{T}.$$

The total E.M.F. will be $\dfrac{(\phi_1 + \phi_2)\Delta S}{T}$.

We have seen that we must have

$$\frac{(\phi_1 + \phi_2)\Delta S}{T} = \frac{(L + M)I}{T}$$

or

$$(\phi_1 + \phi_2)\Delta S = (L + M)I.$$

If we write $\dfrac{\phi_1 + \phi_2}{2} = \phi$ we get

$$2\phi\Delta S = (L + M)I$$

and

$$\phi = \frac{(L + M)}{2}\,\frac{I}{\Delta S}.$$

This shows that there is a relation between the coefficient $\dfrac{L + M}{2}$ and the average value of the magnetic field produced by the total armature winding for unit current in the interval between two coils in the region under commutation. The value $\dfrac{\phi_1 + \phi_2}{2} = \phi$ is approximately situated on a cylindrical surface at half-slot depth, and this surface may be termed the *magnetic periphery* of the armature.

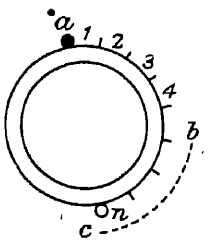

FIG. 10.—Armature with single coil.

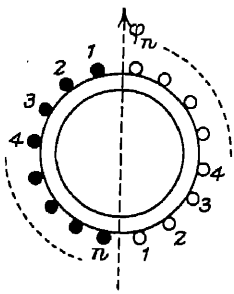

FIG. 11.—Armature with n evenly spaced coils.

In order that the relation that must necessarily exist between the average value ϕ and $(L + M)I$ may be more apparent, let us consider Figs. 10 and 11. On the former a single coil is shown, 1, n, and on the latter n evenly spaced coils, the distance between them being ΔS. The relative direction of the current with regard to the plane of the paper, is shown by the shading.

If, in Fig. 10, the semicircle *abc* is divided into *n* equal parts, 1, 2, 3 . . . *n*, and if ψ represents the average values of the field in each division, then by definition we have

$$LI = \Sigma\psi\Delta S = \Delta S\Sigma\psi.$$

It will be seen at once that in Fig. 11 the average field ϕ, when all the coils are traversed by a current I, will be $\phi = \Sigma\psi$, because the field ϕ is that for space 1 in the case of coil 1, space 2 in the case of coil 2, etc., and the various values of ψ in the case of Fig. 10 are summed up in Fig. 11. Hence $LI = \phi . \Delta S$.

For two layers of conductors, as is the case in commutator armatures, $\frac{L + M}{2} I = \phi\Delta S$.

More generally, the coil S_1 passing into commutation is traversed by a flux $(L + M)\frac{I}{2}$. The coil S_2, which is passing out of commutation, is traversed by the same flux, but of opposite sign. It follows that the variation of flux which S_1 will have to undergo when moving to the position S_2 will be $(L + M)I$. This flux variation must necessarily be equal to $2\phi\Delta S$, hence we have $\phi\Delta S = \frac{(L + M)}{2}I$.

Study of E.—From the above remarks it will be seen that, in every case, the condition for perfect commutation will be

$$E_p = (L + M)\frac{I}{T}.$$

E is a composite quantity, and can be written as $E = E_1 + E_2$

E_1 is the E.M.F. produced in the short-circuited sections by rotation of the armature in the fields of the stator, with or without special compensating windings, auxiliary poles, etc.

E_2 is the E.M.F. produced from the fact that the armature is rotating in an enclosing body with a variable air-gap. In the absence of salient poles (induction and commutator motors) the armature flux, that is, the resultant flux of the various non-short-circuited armature coils, does not pass through the short-circuited coils. This is obvious, because the axis of the armature flux lies in the plane of the short-circuited coils. This, of course, means that there is no mutual induction between the

short-circuited sections and the remainder of the armature. In the case of salient poles, on the contrary, there are only two brush positions for which the armature flux does not pass through the short-circuited coils. These two positions are those for which the armature ampere-turn vector is perpendicular to the polar axis (minimum permeability) or coincident with the polar axis (maximum permeability).

For any intermediate position such as that shown in Fig. 12, a portion of the armature flux passes through the short-circuited coils. Hence, there will be a certain mutual induction coefficient N between the coils under commutation and the armature as a whole.

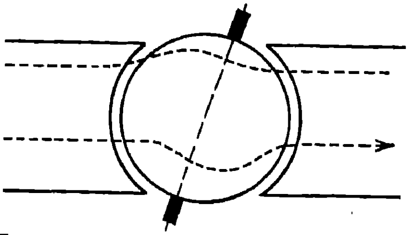

FIG. 12.—Intermediate position with armature flux passing through short-circuited coil.

Now this coefficient is variable during the time of commutation, hence an E.M.F. will be produced in the coil, and its value will be

$$E_2 = I\frac{dN}{dt}.$$

It should be noted that this E.M.F. is favourable to commutation. In other words, the absence of iron in the inter-polar spaces is a favourable condition for good commutation, but can never be so for *perfect* commutation.

Generally speaking, then, it may be stated that for an armature rotating within an enclosing frame, bearing a current I, and with a variable air gap, it is necessary to see whether there is not a mutual induction coefficient N between the short-circuited coils and the remainder of the armature which gives rise to an E.M.F.

$$E_2 = I\frac{dN}{dt}.$$

Study of $e = E - E_p$.—The above remarks on E_p and E have, of course, determined e, but e may be studied more directly.

Let ϕ represent the average value of the resultant field of

all armature and static fields at the magnetic periphery of the armature, and through the surface ΔS comprised between two coils under commutation. We may write

$$e_{\text{average}} = n\frac{\phi \Delta S}{T}$$

where n is the number of turns per coil.

This equation results from the following considerations. The coil S_1 passing into commutation carries a resultant flux ϕ_1, the coil S_2 passing out of commutation, a flux ϕ_2. During the process of commutation, the coil S_1 takes the place of S_2. The variation of flux $\phi_2 - \phi_1$ in coil S_1 will be

$$\phi_2 - \phi_1 = n\phi\Delta S,$$

whence

$$e_{\text{average}} = n\frac{\phi \Delta S}{T}.$$

In order to obtain $e_{\text{average}} = 0$, the condition is necessarily $\phi = 0$, *so that perfect commutation will occur for* $\phi = 0$.

It will be seen from this that e depends on ϕ. Even assuming the machine to be at rest, the knowledge of the currents in the stator circuits will lead to the knowledge of the resultant flux ϕ at the magnetic periphery of the armature where commutation occurs as soon as the armature rotates. In order to study the conditions of commutation, one will then consider the independent action of $e = n\phi\frac{\Delta S}{T}$.

Here it is that we will have to take into consideration $Zv\frac{\Delta}{\Delta_1^1}$ in order to obtain $S_{a,\,T}$, and the values of e, Z, v, $\frac{\Delta}{\Delta_1^1}$ are critical values, as has been shown in Part I.

Either by the use of auxiliary poles, or by shifting the brushes, ϕ will be reduced as near zero as possible. In order that, under practical conditions, e should be different from zero, $\frac{\Delta}{\Delta_1^1}$ will be kept as small as possible.

In the case of rectangular brushes, when perfect commutation corresponds to a linear variation of current, it may be shown that, if e is constant, the energy liberated in the short-circuited coil is independent of I.

In the case of alternating current, other E.M.F.'s must be considered.

We can still write

$$E_p = \frac{(L + M)I}{T},$$

where I represents the instantaneous value of the current under commutation, but the actual E.M.F. E will comprise the E.M.F. which may exist, due to the static variation of the stator or armature fields.

The only general law which still holds good is that, at any given instant, in order that we may have $e - E - E_p = 0$, then, the coil under commutation must, before and after being short-circuited, be traversed by an equivalent resultant flux.

In concluding this chapter on commutation, it is necessary to examine two special cases which have a direct bearing on alternating current commutation.

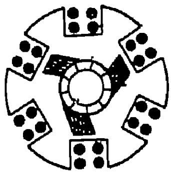

FIG. 13.—Armature with twelve coils in six slots and three brushes. (Squirrel-cage commutation.)

They are :—

1. What may be called squirrel-cage commutation, in which, whatever the position of the commutator may be, there is at least one coil under short-circuit in each slot.

2. Commutation for multiple-winding armatures.

Squirrel-cage Commutation.—Fig. 13 shows an armature winding with twelve coils in six slots, and three brushes α, β, γ, 120° apart, the width of each brush being greater than that of a segment.

Under these conditions, for two opposite slots, there will be four coils, one of which, at least, is short-circuited. In other words, there will always be a short-circuit under the brushes, and the short-circuit current is passed on from brush to brush without sparking.

In this case, of course, $\frac{\Delta}{\Delta_1^1}$ is practically equal to zero.

If the number of brushes is odd, the number of slots must at most be equal to twice the number of brushes.

Such conditions may be obtained with five brushes 72° apart, and a maximum of ten slots, or with seven brushes,

$51\frac{3}{7}^\circ$ apart, with a maximum of fourteen slots, or nine brushes 40° apart with a maximum of eighteen slots.

If we double the number of brushes and, instead of 3, 5, 7, 9, use 6, 10, 14, 18, then it is still necessary to keep to a maximum of 6, 10, 14, 18 slots, but there will be two coils per slot short-circuited, and commutation will be better still.

One may say that one has squirrel-cage commutation when—

(1) The number of brushes being odd, the number of slots per pole is at most equal to the number of brushes.

(2) When the number of brushes is even, if the number of slots per pole is at most equal to half the number of brushes.

Where polyphase commutator machines are concerned, the number of brushes is equal to the number of phases used for feeding the rotor. The multiplication of phases has been described elsewhere in this volume.

As an example of a nine-phase rotor giving squirrel-cage commutation, we may mention a Latour motor built by the Ateliers de Jeumont for the Escarpel Mines (France). Several of these were installed, each rated 225 h.p. (50 cycles) with eight poles and seventy-two slots on the rotor. There were nine equidistant lines of brushes. These were three-phase machines.

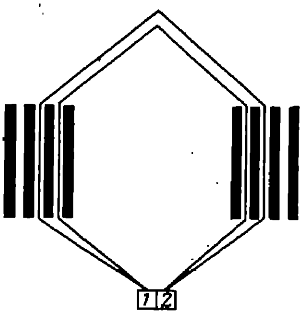

FIG. 14.—Two windings in parallel lying in adjacent slots.

Instead of depending on the number of brushes in order to obtain squirrel-cage commutation, special windings may be designed for the purpose (Latour-Perret).

As shown in Fig. 14, two windings may be used in parallel lying in adjacent slots. In this way, double the number of slots per pole becomes admissible. Moreover, the E.M.F. generated in the two coils is practically the same, and circulation currents are not to be feared. Finally, an arrangement such as that shown in Fig. 15 may be used. An example of a motor with these special windings is the three-phase motor, installed by the Ateliers de Charleroi at the Mines de Bascoup (Belgique). This motor was rated at 350 h.p. (50 cycles), and fed with six phases through only six brushes.

The conclusion is that squirrel-cage commutation is par-

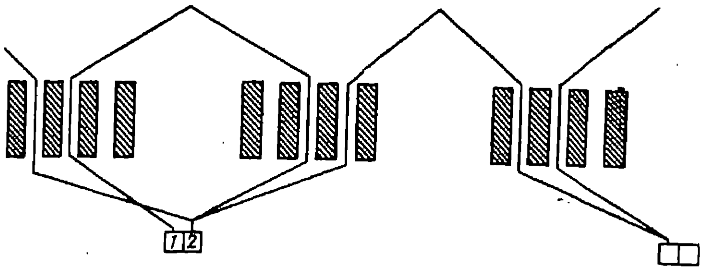

FIG. 15.—Special winding for squirrel-cage commutation.

ticularly interesting for alternating current machines, and that there is a great future in its application and development.

Multiple Winding Commutation.—By multiple windings are meant a number of independent windings connected to separate

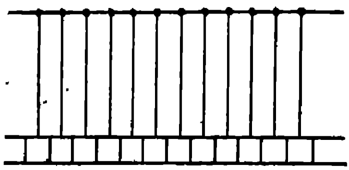

FIG. 16.—Multiple winding commutation, single winding.

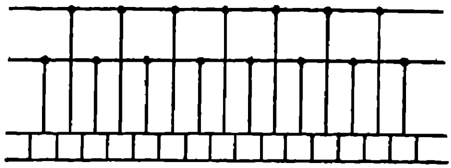

FIG. 17.—Multiple winding commutation, double winding.

commutator segments and paralleled by the brushes.

Single, double, and triple windings of this type are shown in Figs. 16, 17, and 18 respectively.

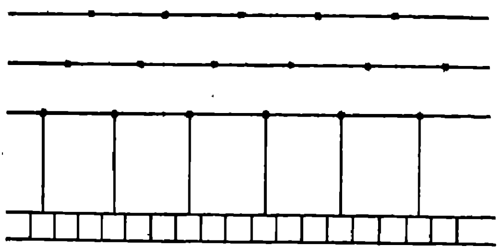

FIG. 18.—Multiple winding commutation, triple winding.

As far as direct current machines are concerned, the use of windings of this type has not always proved a success. The reason for this is that for equal sub-divisions of the commutator, multiple windings have more self-induction.

Comparing a single winding comprising one turn per slot with a double winding comprising two turns per slot, the brushes covering two segments, if we form $\frac{\Delta}{\Delta_1^1}$ we will obviously obtain a value four times as great for the double as for the single winding. The double winding will not, therefore, be as favourable to commutation as the single winding.

In fact, the sub-division on the commutator for a multiple winding is devoid of any real meaning, and, as far as commutation is concerned, it is equivalent only to the number of segments corresponding to a single winding.

If, on the other hand, we connect to the commutator segments an equal number of equipotential points on the windings, the multiple winding becomes equivalent to an ordinary single winding, because the windings are no longer *parallelled* by the brushes. This explains the beneficial influence of equipotential connections in series—parallel windings.

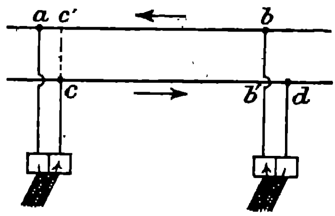

FIG. 19.—Short-circuit conditions with a multiple winding.

The true importance of multiple windings lies in their application to alternating current machines with a view to avoiding short-circuit currents under the brushes. It is often erroneously supposed that multiple windings entirely do away with short-circuits, since there is no direct connection between segments connected to any one coil. This is, of course, quite incorrect. Turning to Fig. 19, at the instant when brushes α and β overlap two segments, coils *ab* and *cd* are connected in parallel, but the E.M.F.'s in these two coils are not exactly equal. They differ by an amount equal to the geometrical sum of the voltages in the half-coils *ac'* and *b'd*. The inevitable result will be a circulation current which exactly corresponds to the short-circuit current in a single winding. The only favourable point is that this current will, in fact, be limited by the resistance of $ab - dc$.

In other words, commutation with a multiple winding comprising p elements, and for which $p - 1$ segments are covered,

corresponds to that for a single winding with a similar number of segments, and very resistant connections.

More precisely, if we consider a bi-polar double winding with two brushes at 180°, then such an arrangement will be equivalent to a single winding, with connections between armature and commutator of equal resistance to the total resistance of the armature. In the case of a triple winding, this would be equivalent to a single winding with connections of resistance equal to $^3/_2$ times the armature resistance.

From the point of view of efficiency, to obtain the same total losses with an equivalent single winding as with a multiple winding, one must assume that the resistant connections are the only resistances, and that the single winding considered is non-resistant. This will be obvious when we consider that, in the case of a multiple winding, it is the resistant connections that are, so to speak, distributed over the armature to form the winding. It will at once be apparent that there will be a gain of efficiency in the case of multiple windings.

Commutation with multiple windings can be compared to that with a single winding in which the armature-commutator connections possess not only resistance, but a certain amount of self-induction.

In practice, the E.M.F. due to the self-induction of these imaginary connections may be counteracted by a suitable commutation field, acting at *ac'* and *b'd* (Fig. 19). Hence there is no reason why the use of multiple windings should not give just as good results as the use of a single winding with high-resistance connections.

The trouble really lies with the method of winding.

If we are using a multiple winding comprising p elements, and we consider the instant in which the brushes are covering $p - 1$ segments, then we have $p - 1$ windings in circuit, and one winding out of circuit. If the commutator now rotates to the extent of one segment, a new winding comes out of circuit, whereas the one that was out of circuit comes into circuit.

In order that this substitution should take place under the best possible conditions, the total current in each slot should remain the same before and after substitution. To obtain this result, each winding must be represented in each slot by an

equal number of conductors. Moreover, on account of the substitution in those slots where commutation occurred with a simple winding, that is in the slots containing *ac'* and *b'd* (Fig. 19), there is an exchange by which conductors belonging to one winding, and carrying armature current in a certain direction, are replaced by conductors belonging to a second winding, and carrying current in the opposite direction. It follows that the total current will vary in these slots just as it varies in the slots containing the coils under commutation of a single winding.

A perfect arrangement of the winding in the slots will be such that for any angular displacement of the commutator to the extent of one segment, the same total current variation will occur in those slots where commutation is taking place exactly as though a single winding was concerned.

It will be found otherwise that certain of the segments will bear the brunt of commutation while others are comparatively idle.

These remarks conclude the theoretical examination of the phenomenon of commutation and, it is hoped, may prove of some use, both for the clearer comprehension of alternating current commutator work and for the design of commutator machines, and what we have termed squirrel-cage and multiple windings.

CHAPTER III.

ANALYTICAL TREATMENT OF THE THEORY OF THE SIMPLER FORMS OF SINGLE-PHASE AND REPULSION COMMUTATOR MOTORS.

MOTORS of the repulsion, compensated repulsion, Latour, and single-phase series types have been described by various authors, and the present contribution to the theory of these simpler forms will not add much to what has already been said about them. A description of the various forms of early commutator motors, however, is just as indispensable to the present work as is, indeed, the exposition of the theory of the repulsion motor, as a basis from which we may work up to more elaborate types.

The different diagrams given in Fig. 41 will give the reader a very fair idea of the various forms of these early motors, and also of the process by which they were gradually developed from the original simple forms. The fact that a great many investigators developed various types of motors simultaneously in different countries has made it very difficult to give any definite name to the types described. A typical example of this is the type known as the Latour-Winter-Eichberg motor, which was invented about the year 1900 by Winter and by Eichberg in Germany, and by Latour in France. In our opinion, the use of such names for describing a number of types which can hardly be said to differ materially from one another can only lead to confusion, since what may be described by one author as the Winter motor may be described by another as the Latour motor, or, with some slight addition or variation, as some totally different type. We have confined ourselves, therefore, to the description of a certain number of classes, under which all commutator motors may be divided, and have not attempted to give them any names, other than such tech-

nical names as may properly define their position in the classification we have introduced. Pending the more complete classification that will follow in due course, we may state that all early forms of the commutator motor, as well as most modern forms, excluding polyphase motors, fall under the following headings :—

1. The ordinary repulsion motor.
2. The compensated repulsion motor.
3. The single-phase series motor.
4. The compensated single-phase series motor.

A brief exposition of the theory of these various types will be sufficient to cover the theory of every variation of these forms, and will constitute a sound and convenient basis for the theory and closer study of the polyphase types.

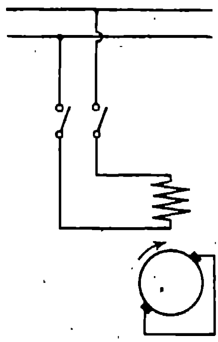

FIG. 20.—Elihu Thomson's motor.

Before considering the theory of these motors, it would be well to say, that, to the best of our belief, the first appearance of the repulsion motor dates back to 1887, and is due to Professor Elihu Thomson, who took out U.S.A. Patents Nos. 363,185 and 363,186, on January 26th of that year.

Fig. 20 gives a diagrammatical representation of this motor. It comprises a primary winding on a stationary field, and a secondary winding on a commutator armature, there being one pair of brushes per pair of poles. Positive and negative brushes are simply short-circuited, and there is no connection with the supply circuit except from the field winding.

If we consider the motor at rest, and the field fed from an alternating current supply, a current will be induced in the rotor winding, the circuit being closed by the connection from positive to negative brush.

This current will be practically in quadrature with the field current, as would be the case for an ordinary transformer. The rotor will start up in the direction shown on account of the torque resulting from the mutual action of the field and armature currents, and this torque is quite similar to that of a direct

current series motor in which the brushes would be set at a certain angle lagging with regard to the direction of rotation.

General Theory of the Single-phase Commutator Motors.—In order to understand the operation of the repulsion motor, it is essential to consider the fact that there are two electromotive forces induced in the armature, both of which have a frequency ω, which is the frequency of the mains.

The first of these, which we will call the *static electromotive force*, arises from the mutual induction between primary and secondary, and is due to a *transformer effect*. The second one, which we will call the *dynamic electromotive force*, arises through the rotation of the armature through the alternating field. Before calculating the value of these electromotive forces, which will lead us to a first conception of the diagram of the repulsion motor, it is necessary to establish a preliminary point.

Let us consider two circuits, with self-induction respectively equal to L_1 and L' and a mutual induction coefficient M. If i_1 and i_2 are the currents at any given instant t, then the electromotive force induced in the first circuit will be

$$L_1\frac{di_1}{dt} + M\frac{di_2}{dt}.$$

This can be written

$$L_1\left(\frac{di_1}{dt} + \frac{d\frac{M}{L_1}i_2}{dt}\right) = L_1\frac{d}{dt}\left(i_1 + \frac{M}{L_1}i_2\right).$$

It is as if there were no mutual induction between the two circuits, and the first circuit retained its self-induction L_1, while the current i_1 was increased by a quantity

$$\frac{M}{L_1}i_2 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Now, returning to the simple repulsion motor, if the brushes lie on the neutral line, the mutual induction coefficient between the field and armature is equal to zero; hence no current will be induced in the armature by the alternating current flowing through the stator, and, consequently, the torque will be equal to zero. If, on the other hand, the brushes coincide with the poles, the mutual induction coefficient is at a maximum, and

the alternating current flowing through the stator or field will induce a current in the rotor or armature which acts as the secondary short-circuited winding of a transformer. But here, again, no torque will be developed, because the direction of the magnetic flux produced by the current induced in the rotor is coincident with the flux produced by the current in the stator.

In any intermediate position, however, a torque will arise. It will be easy to show that the rotor will rotate in the opposite direction to that in which the line of brushes lies with regard to the zero-torque line. Let OA (Fig. 21) represent the stator flux at a given instant t. This can be split up into two components, the one, OB, in line with the brushes; the other, OC, perpendicular to that line. From Lenz's law, the armature flux tends to annul the stator flux, and will therefore lie along OD.

It is all as though the armature had a North pole N′ and a South pole S′. There will be *repulsion* between N and N′, and between S and S′, and rotation will take place as shown.

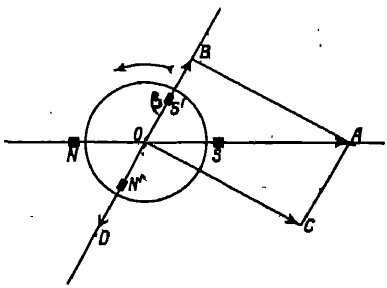

FIG. 21.—Components of stator flux.

We will return in a little while to this point, and in a later chapter we will show the significance of the two rest positions when the brushes coincide with the polar axis, or with a perpendicular to the polar axis.

Let us now calculate the two voltages we defined above; we will call E_2 the static electromotive force, and E_2^1 the dynamic electromotive force.

If the brushes are moved through an angle β from the neutral line, the mutual induction becomes

$$M \sin \beta.$$

At any given instant, the static electromotive force will be

$$e_2 = -M\theta \sin \beta \frac{di_1}{dt} \quad (\theta = \text{angular velocity})$$

whence

$$E_2 = M\theta I_1 \sin \beta.$$

At any given instant, the dynamic electromotive force will be

$$e_2^1 = M\omega \cos \beta i_1,$$

whence

$$E_2^1 = M\omega I_1 \cos \beta.$$

Let Z_2 be the short-circuited armature impedance, and I_2^1 and I_2 the currents that correspond to E_2^1 and E_2.

$$I_2 = \frac{M\omega I_1 \sin \beta}{Z_2}$$

$$I_2^1 = \frac{M\omega I_1 \cos \beta}{Z_2}.$$

These currents will then be lagging or leading by an angle $\gamma = \frac{L_2\omega}{R_2}$ where R_2 is the resistance between the brushes. Bearing in mind our preliminary remark (1), we get

$$J_2 = \frac{M \sin \beta}{L_1} I_2 = \frac{M^2\omega \sin^2 \beta}{L_1 Z_2} I_1$$

$$J_2^1 = \frac{M \sin \beta}{L_1} I_2^1 = \frac{M^2\omega \sin \beta \cos \beta}{L_1 Z_2} I_1.$$

Let us take OA (Fig. 22) as the origin of phases, this being

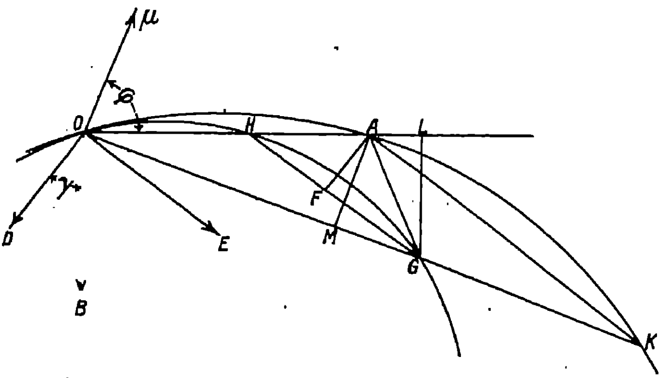

FIG. 22.—Diagram of the simple repulsion motor.

the phase of the primary current.

The static electromotive force e_2 will lie along OB, and the dynamic electromotive force e_2^1 along OA.

The secondary currents, expressed according to definition 2, J_2 and J_2^1 will lie along OD and OE, these lines forming a right

angle between themselves, and at an angle γ with OB and OA respectively.

To obtain the fictitious primary current produced by the superimposition of the real current i_1 and the two currents J_2 and J_2^1, let us draw

$$OA = I_1 \qquad AF = OD = J_2 \qquad FG = OE = J_2'.$$

OG represents the fictitious primary current I_0, which would alone produce the total electromotive force, which force is due, in the actual motor, to the self-induction of the primary, and the mutual induction of the secondary and primary.

This electromotive, or, rather, counter-electromotive force is L_1I_0, and one may write

$$U = L_1I_0,$$

U being the constant voltage applied to the motor. It will be seen that, though somewhat complicated in form, the above remarks lead us to very simple results.

It follows immediately that I_0 or OG is constant. Let us prolong GF to H. Then

$$OHG = \pi - \gamma.$$

Now we have

$$AH = \frac{AF}{\sin\gamma} = \frac{M^2\omega\sin^2\beta}{L_1Z_2\sin\gamma}I_1$$

and

$$OA = I_1$$

whence

$$\frac{OH}{OA} = 1 - \frac{AH}{OA} = 1 - \frac{M^2\omega\sin^2\beta}{L_1Z_2\sin\gamma}.$$

This ratio is constant, whence it follows that if, through A, we draw AK parallel to HG, OG being constant, OK will also be constant, and since K is fixed, and angle OAK $= \pi - \gamma$ is constant, A will describe the arc of a circle.

We have

$$\sin\gamma = \frac{L_2\omega}{Z_2},$$

$$\frac{OG}{OK} = \frac{OH}{OA} = 1 - \frac{M^2\sin^2\beta}{L_1L_2} = \sigma,$$

which has been called the coefficient of dispersion of the motor.

The primary voltage U, which is equal to $L_1\frac{di_0}{dt}$, is in quadra-

ture with OG, and leading, and can therefore be represented by OU, and, consequently, the lagging or leading angle ϕ will be represented at any moment by UOA.

We can also represent on this diagram the angular velocity, the torque, and the power.

$$FG = J_2^1 = \frac{M^2\theta \sin\beta\cos\beta}{L_1 Z^2} I_1$$

$$AF = J_2 = \frac{M^2\omega \sin^2\beta}{L_1 Z^2} I_1,$$

whence

$$\frac{FG}{AF} = \tan . FAG = \frac{\theta}{\omega \tan . \beta}.$$

The angular velocity is therefore (for a definite value of β) proportional to tan FAG.

The power may be calculated as for a direct current machine:

$$p = M\theta i_1 \cos\beta i_2$$

$$P = M\theta \cos\beta \frac{1}{T}\int_0^T i_1 i_2 dt = M\theta \cos\beta I_1 I_2 \cos\lambda$$

where λ is the lag of I_1 over I_2.

The torque will then be

$$\begin{aligned} C &= M\cos\beta\cos\lambda I_1 I_2 \\ &= L_1 I_1 \frac{M\sin\beta}{L_1} I_2 \cos\lambda \cot . \beta \quad . \quad . \quad \text{(see 1)} \end{aligned}$$

From G drop a perpendicular GL to OA,

$$C = L_1 . \overline{OA} . \overline{AL} . \cot . \beta.$$

The torque is therefore represented by the product of $\overline{OA}$ and $\overline{AL}$.

Finally, the total power $UI_1 \cos . \phi$ is obviously proportional to the area of triangle OAG, and hence, since OG is constant, proportional to AM.

Additional Remarks.—The theory of the ordinary repulsion motor can be considered from a slightly different point of view.

A. Conditions at Rest.—Turning to Fig. 23, the effective current in the stator can be represented by the vector OS, the

length of which will be proportional to the total ampere turns. We can split this vector up into two components, the one, $\overline{OS_1}$, in the direction *cd*; the other, $\overline{OS_2}$, at right angles to the former.

On account of the existing short-circuit, the first of these, by static induction, will give us a vector OR, which corresponds to a damping current in the armature, and will be equal to, and in direct opposition with, $\overline{OS_1}$.

The vector $\overline{OS_2}$, therefore, alone represents the resulting ampere turns, and by multiplying this vector by 4π and dividing it by the reluctance R of the magnetic circuit, we will get the effective flux in the machine.

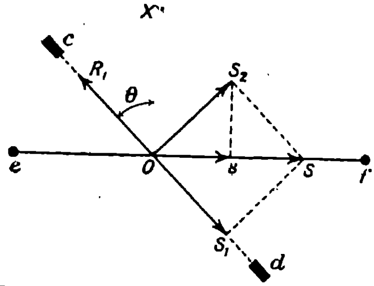

FIG. 23.—Components of effective current in stator.

This flux in turn may be considered as made up of two components at right angles to one another lying along *ef* and OX respectively.

The component $\frac{4\pi}{R}\overline{OS}$ gives rise to an electromotive force equal and opposite to that between the stator terminals. Calling N and V the supply frequency and voltage, we can write

$$nN\frac{4\pi}{R}\overline{OS} = V,$$

where *n* is the number of stator turns.

From this equation we will get $\overline{OS}$, and the vector diagram in Fig. 22 can be drawn for any given position of the brushes defined by $\widehat{COX} = \theta$.

Torque.—The torque will be equal to the product of the flux $\frac{4\pi}{R}\overline{OS_2}$, at right angles to the brush line, by vector $\overline{OR}$, which represents the rotor current ampere-turns. The torque may then be expressed as follows:—

$$\frac{4\pi}{R}\overline{OS_2} \times \overline{OR_1}.$$

From Fig. 22 we immediately obtain

$$\overline{OS_2} = \frac{Os}{\cos.\theta}, \qquad \overline{OR_1} = \frac{Os}{\cos.\theta}\tan.\theta.$$

The torque will then be equal to

$$\frac{4\pi}{R}\overline{Os}^2\frac{\sin.\theta}{\cos^3.\theta}.$$

It will be seen from this expression that the torque will increase very rapidly and indefinitely as angle θ increases. There will, of course, be a limiting effect on account of leakage in the magnetic circuit, and ohmic resistances which we have neglected in the above remarks. Once this limit has been reached, the torque will begin to decrease for a further increase of θ, but the current will continue to increase and may rise to dangerous values.

Starting Current—Ratio of Starting Torque to Current.—From Fig. 23 we see that $\overline{OS} = \frac{Os}{\cos^2.\theta}$. The starting current is therefore proportional to $\frac{1}{\cos^2.\theta}$ and the ratio of the starting torque to the starting current will vary as $\tan\theta$.

B. Conditions when Running.—The diagram shown in Fig. 23 is still applicable when the motor is running, but we must consider the addition of a new electromotive force in the rotor due to the rotation of the armature within the stator field (along OS_2). This is the dynamic electromotive force we defined earlier in this chapter.

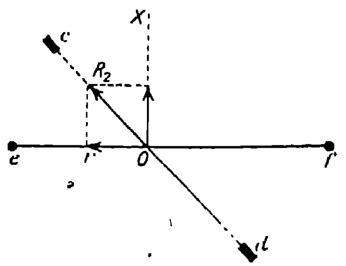

FIG. 24.—Components of secondary flux.

The current corresponding to this E.M.F., which will be a short-circuit current, is in quadrature with the E.M.F. producing it. It is also in quadrature with the field lying along OS_2, that is, with the stator current. This new current is represented by the vector $\overline{OR_2}$ in Fig 24.

If N_1 is the number of revolutions per second, then

$$\overline{OR_2} = \frac{N_1}{N}\overline{OS_2}.$$

In addition to the effective flux $\frac{4\pi}{R}\overline{OS_2}$ lying along OS_2, we now have a second flux lying along *cd*, its value being

$$\frac{4\pi}{R}\frac{N_1}{N}\overline{OS_2}$$

and in quadrature in time and space with the former. This second flux splits up into two components, one of which, $\frac{4\pi}{R}Or$, lies along *ef*, and the other along OX (Fig. 24). The component $\frac{4\pi}{R}Or$ alone induces an E.M.F. in the stator, and this E.M.F. is in phase opposition with the stator current, its value being $nN\frac{4\pi}{R}\overline{Or}$.

This E.M.F. is in quadrature with the wattless E.M.F. induced by $\frac{4\pi}{R}\overline{Os}$ mentioned above (Fig. 23).

To obtain the resultant of these two E.M.F.'s, we must write

$$V = nN\frac{4\pi}{R}\sqrt{\overline{Os}^2 + \overline{Or}^2}.$$

From Fig. 23 we get

$$\overline{OS_2} = \frac{\overline{Os}}{\cos.\theta}$$

and from Fig. 24

$$\overline{Or} = \overline{OR_2}\sin.\theta = \frac{N_1}{N}\overline{OS_2}\sin.\theta,$$

whence

$$\overline{Or} = \frac{N_1}{N}\overline{Os}.\tan.\theta,$$

hence

$$V = nN\frac{4\pi}{R}\overline{Os}\sqrt{1 + \left(\frac{N_1}{N}\right)^2\tan^2.\theta}.$$

If N and V, N, and θ are given, then Os may be got from the above equation, and the various characteristics of the motor may be calculated as before.

Torque.—This is again expressed by the product

$$\frac{4\pi}{R} \times \overline{OS_2} \times \overline{OR_1},$$

that is,

$$\frac{4\pi}{R} \cdot \overline{Os^2} \times \frac{\sin . \theta}{\cos^3 . \theta}.$$

Substituting the value of $\overline{Os^2}$ we get

$$\frac{V^2}{\frac{4\pi}{R} n^2 N^2} \times \frac{\sin . \theta}{\cos^3 . \theta} \times \frac{1}{1 + \left(\frac{N_1}{N}\right)^2 \tan^2 . \theta}.$$

For any given position of the brushes, the ratio between the starting torque and the torque at full speed will be, from the above expression,

$$1 + \left(\frac{N_1}{N}\right)^2 \tan^2 . \theta.$$

Current Drawn from Mains.—The value of the current drawn from the mains will vary as $OS = \frac{Os}{\cos^2 . \theta}$ that is, as

$$\frac{1}{\cos^2 \theta \sqrt{1 + \left(\frac{N_1}{N}\right)^2 \tan^2 . \theta}}.$$

Power Factor.—The power factor is the ratio between the electromotive force induced by the flux $\frac{4\pi}{R} \times \overline{Or}$, in phase with the stator current, and the supply voltage V.

$$\cos . \phi = \frac{\frac{N_1}{N} \tan . \theta}{\sqrt{1 + \left(\frac{N_1}{N}\right)^2 \tan^2 . \theta}}$$

or, in a simpler form,

$$\text{Cotan } \phi = \frac{N_1}{N} \tan . \theta.$$

At synchronism, $N_1 = N$, and

$$\text{Cotan } \phi = \tan . \theta$$

$$\phi = \frac{\pi}{2} - \theta.$$

Example.—In this particular instance the brush-setting angle has a concrete meaning. If, for instance, we take for θ a value somewhere near 64°, then

$$\tan \theta = 2,$$

and at synchronism,

$$\cos \phi = 0{\cdot}89.$$

The starting torque in this case will be equal to five times the normal torque.

The starting current will be equal to $\sqrt{5}$ times the normal current.

Commutation.—From what has been explained above, it is clear that there are two fluxes, $\overline{OS_2}$ and $\overline{OR_2}$, lying along $\overline{OS_2}$ and *cd*, and their ratio is

$$\frac{\overline{OR_2}}{\overline{OS_2}} = \frac{N_1}{N}.$$

At synchronism these fluxes are therefore equal and the total resulting flux in the motor is a true rotating field. Under these conditions, commutation will be perfect, and the commutator will be equivalent to a continuous slip-ring. The rotating field may be shown by a rotating vector,

$$\overline{OS_2} \times \frac{4\pi}{R} \times \sqrt{2}.$$

The foregoing theory does not take into consideration magnetic leaks, ohmic resistances, or harmonics, but the results are sufficiently near what occurs in actual practice, and have been experimentally verified on actual motors.

Compensated Single-phase Motors of the Latour Type.—It has been a general rule with authors to treat the repulsion motor, the Latour motor, and the series and shunt single-phase motors as entirely separate entities, and to develop elaborate theories and diagrams for each type. We have found it preferable to treat all commutator motors as a single class, as far as their fundamental theory is concerned, and by this means to pass on from the ordinary repulsion motor through the Latour motor to the series and shunt motors by a gradual elaboration of the original theory. This presents the double advantage of linking up what many readers have hitherto considered as separate

types, and of emphasising those fundamental properties which are characteristic of commutator machines.

If we sum up the properties of the repulsion motor, we find that commutation is perfect only at synchronism, where a true rotating field is obtained: that, generally speaking, the motor behaves just like a direct-current series motor.

The applications in practice of such a motor will be limited for these reasons, and, moreover, the power factor is low at medium and low speeds.

The idea of using compensation on repulsion motors is an old one, and many forms of such motors were designed, as a glance at Fig. 41 will show.

The greater number of these forms have long been obsolete, and are worthy of the short mention given them only on account of their historical interest.

The method used for applying compensation does not effect the theory of compensation, and any of the types shown would answer equally well. We have chosen the Latour type of compensated motor because the method employed has proved to be the best, because motors of this type have been, and still are, extensively used, and, finally, because the theory of compensation as applied to these motors will lead us quite naturally to the consideration of series and shunt types of single-phase motors as a preliminary to the discussion of the polyphase type in a later chapter.

The Latour type of motor was designed in order to obtain a unity power-factor over a wide range of speeds, and, by altering the rotor and stator connection, to give similar characteristics to the series and shunt types of direct-current motors.

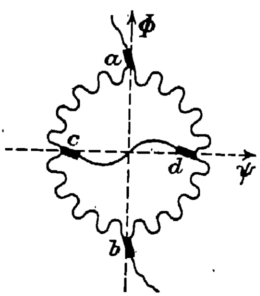

FIG. 25.—Simple commutator armature.

Let us consider a commutator armature (Fig. 25), which we will assume lies in a magnetic field, and let us feed it with an alternating current I through two diametrically opposed brushes *a*, *b*. This current will give rise to a flux Φ in the direction *a*, *b*.

If we now provide a second pair of brushes, *c*, *d*, the line of

these brushes being at right angles to the line of the other two, as soon as the armature rotates, a dynamic electromotive force will be induced between brushes *c* and *d* owing to the presence of the field Φ.

This electromotive force will consequently be in phase with the current I, and if we connect *c* and *d* together, a current J will flow in the rotor, which will be 90° out of phase with I (ohmic resistances are here, as elsewhere, neglected).

The current J will produce a flux ψ, and, along *ab*, we will have

$$\psi = \frac{N_1}{N}\Phi \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The meaning of this equation is, that the electromotive forces induced in the circuit *cd* by the fluxes ψ and Φ balance one another. These fluxes are, of course, in quadrature in time, as are currents I and J.

Let us now determine the electromotive force that should be applied to *a*, *b*, to obtain a current I. It will be the geometrical sum of the static electromotive force induced by Φ and proportional to ΦN, and the dynamic electromotive force induced by ψ, proportional to ψN_1, and therefore, on account of equation (2), to $\Phi\frac{N_1^2}{N}$.

The electromotive force applied to *a*, *b*, will be, therefore, proportional to $\Phi\left(N - \frac{N_1^2}{N}\right)$.

At synchronism, $N_1 = N$, and the apparent self-induction of the armature becomes zero, and would be negative for $N_1 > N$.

Moreover, at synchronism, $\psi = \Phi$, and we will get a true rotating magnetic field.

This is the fundamental property which we had already established in the case of the repulsion motor, and it applies quite generally to any commutator armature rotating in a sinusoidal field with the brushes short-circuited. Commutation will therefore be perfect at synchronism.

At any other speed, owing to the presence of ψ, a certain E.M.F. is statically induced in the short-circuited turns under brushes *a*, *b*, and this E.M.F. is in phase with the current I under commutation.

This electromotive force, on account of equation (2), *is a constantly correct compensating electromotive force, and commutation under brushes* a *and* b *will remain very near perfection at all speeds.*

Conversely, the flux Φ induces a static E.M.F. in the short-circuited turns under brushes *c* and *d*. There is a difference here, however, in that although the sign of this E.M.F. is always beneficial to the commutation of J, its value is correct only at synchronism. Below synchronism, it is too high, and above synchronism, too low.

It can now be seen that if such an armature is placed in an ordinary single-phase stator, a motor will be obtained that will run with unity power factor and perfect commutation at synchronism, while the commutation at other speeds will be very nearly perfect.

If the rotor and stator are connected in series, the motor characteristics will be similar to those of a direct-current series motor. If, on the other hand, they are connected in parallel, the characteristics will be those of a shunt-wound, direct-current motor. In both cases, of course, a rotor-stator transformer may be used if desired to reduce the rotor voltage, while enabling the stator to be direct connected to high tension supply mains. These types of single-phase series and shunt motors are exactly similar to the true single-phase motor described later, their peculiarity being that compensation is obtained by the provision of an additional pair of brushes on the commutator.

The Déri Motor.—Before passing on to the single-phase series motor, some mention should be made of the Déri motor, since this belongs to the class of repulsion motors, and is important as being one of the first commutator motors that was extensively used, more particularly for cranes and traction.

The basic difference between the original repulsion motor and the Déri motor will be understood by comparing Figs. 26 and 27. A bibolar arrangement is adopted for these explanatory diagrams for the sake of simplicity.

In the Déri repulsion motor there are two fixed brushes, *a* and *b*, located on the axis of the stator windings, and two movable brushes, *c* and *d*, which, though movable, are always

maintained (in a two-pole machine) diametrically opposite to one another.

In multipolar motors the corresponding brushes of the different pairs of poles are usually connected in parallel with

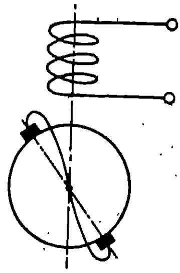

FIG. 26.—Original repulsion motor.

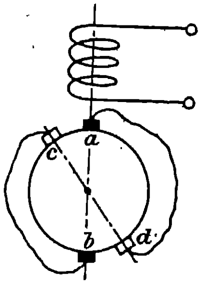

FIG. 27.—Déri motor.

one another. There is no connection between the rotor and the line, either directly or through a transformer.

The Déri motor has been developed by Brown, Boveri & Co., chiefly for crane work and textile machinery, and descriptions of motors of this type will be found elsewhere in this volume;

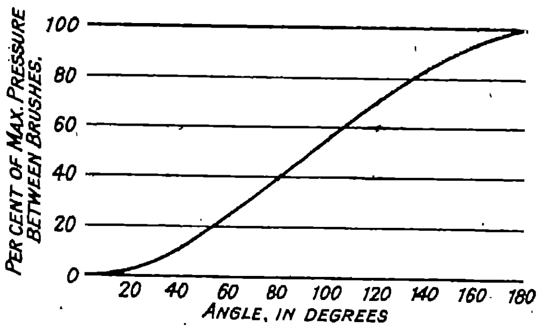

FIG. 28.—Voltage between brushes as a function of angular position.

we are only concerned in this chapter with the analytical treatment of their theory.

It will be at once apparent that the difference of potential between *a* and *c*, and also between *b* and *d*, is a function of the angle spanned by *ac* and *bd*. As this angle is increased from 0° to 180°, the difference of potential rises in accordance with the curve shown in Fig. 28.

The armature will be divided into two regions, that between *c* and *a*, and *b* and *d*, and that between *d* and *a* and *c* and *b*, and consequently the whole arrangement is equivalent to that shown in Fig. 29, in which A represents the stator winding and B and C the two components of the rotor winding.

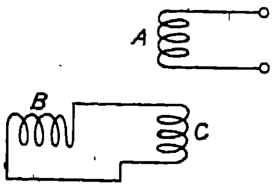

FIG. 29.—Equivalent diagram of Déri motor.

The theory is now exactly similar to that of the compensated repulsion motor, the compensation being variable.

When the rotor is at rest the current flowing into A from the line induces an E.M.F. in C, which results in a current flowing through B and C. The rotor conductors thus lie in two component fluxes, one from A and the other from B.

The conductors of winding C, as a consequence of the current flowing in them, and of the fact that they lie in the field set up by B, experience a torque tending to revolve the rotor.

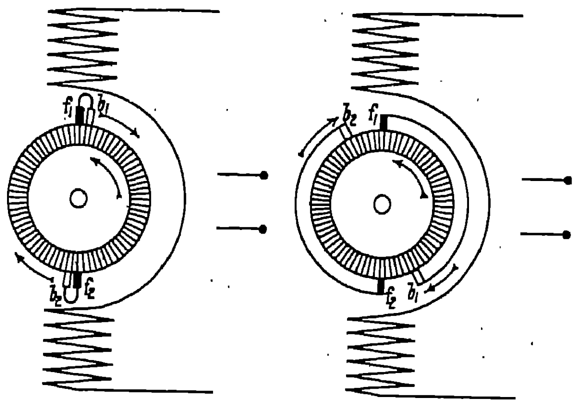
FIG. 30.—Single armature Déri motor.

When the angle between the brushes is reduced to zero, there will flow in A only the magnetising current of the stator. No current will flow in the rotor windings, and there will be no inductive influence exerted on the short-circuited windings. When the angle is increased to some 150° or 160° the starting

torque attains its maximum value with relatively low current consumption.

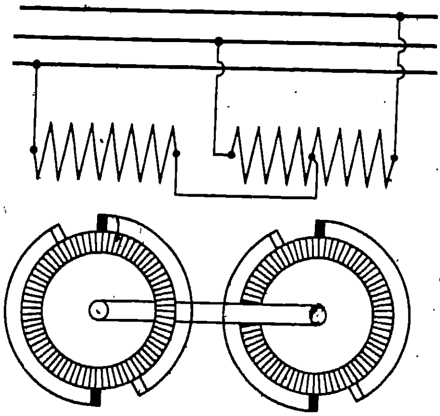

FIG. 31.—Double armature Déri motor.

Figs. 30 and 31 show two forms of the Déri motor, the second being designed with a double armature for use on three-phase

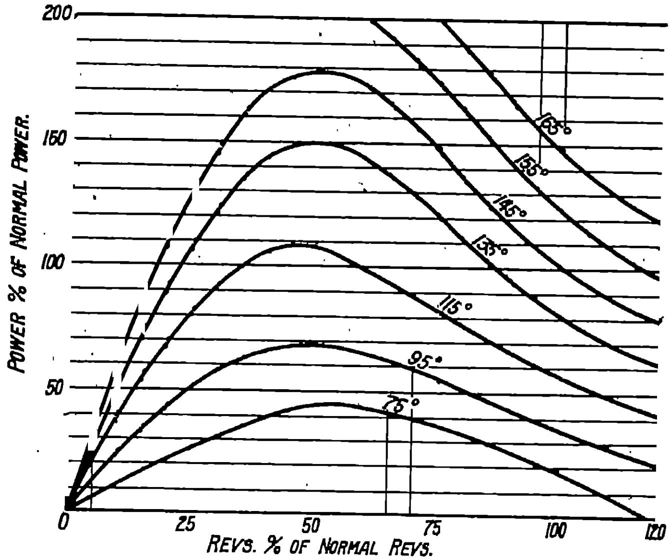

FIG. 32.—Characteristic curves for Déri motor.

systems. It is interesting as the first example of an attempt to use these motors on three-phase systems without undue overloading of any one phase.

Fig. 32 gives a series of characteristic curves for the Déri motor, each curve corresponding to a different brush position. From these, the series character of the motor will be readily recognised.

These motors are merely mentioned here as an important type of compensated repulsion motor, and will be more fully dealt with elsewhere in these pages. They present many points of interest from a practical point of view, particularly as regards smooth starting and speed regulation, and a good power factor over a wide range of speeds. The speed is, of course, as with all repulsion motors, variable by shifting the movable brushes.

The Series Rotor-stator Connection of the Latour Motor.—The series connection of the Latour motor which has been

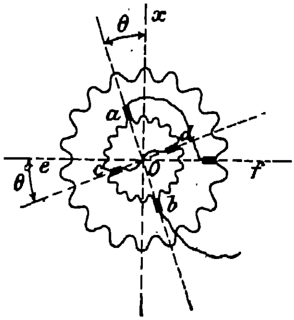

FIG. 33.—The series rotor-stator connection of the Latour motor.

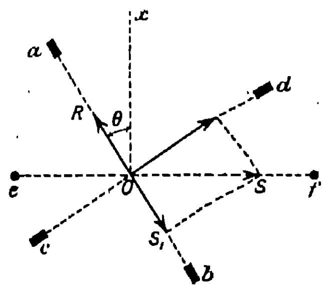

FIG. 34.—Components of stator ampere turns.

described in this chapter is of great interest. It is, in reality, a form of compensated series single-phase motor, and its theory will stand almost without modification for the latter type.

Turning to Fig. 33, let θ be the angle between the short-circuited brushes *cd* and the stator polar axis. Let N_s be the number of turns in the stator winding, and I the current flowing through the motor.

The stator ampere turns may be represented (Fig. 34) by the vector $\overline{OS} = \frac{n_s I}{2\pi}$ lying along *ef*.

This may be split into two components, one of which, lying along *a*, *b*, is

$$\overline{OS_1} = \overline{OS} \sin . \theta,$$

and the other, lying along *cd*, is

$$\overline{OS_2} = \overline{OS} \cos . \theta.$$

The rotor ampere turns may be represented by a vector,

$$\overline{OR} = \frac{n_r I}{2\pi}$$

lying along *ba*.

The sum of the ampere turns taken along *ba* will be

$$\overline{OR} - \overline{OS_1} = \frac{I}{2\pi}(n_r - n_s \sin . \theta),$$

and the flux corresponding to this will be

$$\frac{2}{R}(n_r - n_s \sin . \theta)$$

where R is the reluctance of the total magnetic circuit.

The sum of the ampere turns due to I taken along *cd* reduces to

$$\overline{OS} \cos . \theta = \frac{n_s}{2\pi} \cos . \theta . I,$$

and these ampere turns induce statically a current γ in the circuit *cd*, which is approximately in opposition with I, and the value of which is given by the equation

$$n_r \gamma = n_s \cos . \theta . I.$$

This equation expresses the fact that the current γ is such as to counteract the flux along *cd* due to I.

Owing to the rotation of the armature in the field directed along *ba*, another current J arises which is superimposed to γ in circuit *cd*. This current is in quadrature with I, as in the case of the repulsion motor, and its value is obtained from

$$n_r J = \frac{N_1}{N}(n_r - n_s \sin \theta) I,$$

whence
$$J = \frac{N_1}{N n_r}(n_r - n_s \sin \theta) I.$$

(It would be well to repeat here that N is the frequency of the current I, and N_1 the speed of the motor.)

The current J is alone responsible for the whole of the flux along *cd*, since the flux produced in this direction by I is, as

we have shown, counteracted by the damping flux due to γ. The flux along *cd* will be, therefore,

$$\frac{2\pi_r J}{R} = \frac{2N_1}{RN}(n_r - n_s \sin\theta)I \quad . \quad . \quad . \quad (\alpha)$$

and will be in quadrature with I.

The electromotive force v_1 statically induced by this flux will be in phase with I, and its value will be

$$v_1 = \frac{N_1 n_s}{R\pi}(n_r - n_s \sin.\theta)I.\cos.\theta.$$

The dynamic electromotive force v_2, induced by the same field between brushes *ab*, will be

$$v_2 = \frac{N_r J}{R\pi}N_1 n_r = \frac{N_1{}^2 n_r}{RN\pi}(n_r - n_s.\sin\theta)I,$$

and will lag $\frac{\pi}{2}$ behind I.

Finally, the static electromotive force v_3 induced by the field along *ab* in circuits *ab* and *ef* taken together will be

$$v_3 = \frac{I}{R\pi}N(n_r - n_s \sin.\theta)^2 I,$$

and will be leading I by $\frac{\pi}{2}$.

To obtain the total electromotive force V at the motor terminals, we must take the resultant of the three electromotive forces, v_1, v_2, and v_3.

Now v_1 and I being in phase with one another, and v_2 and v_3 in quadrature with I, then

$$V = \sqrt{v_1{}^2 + (v_3 - v_2)^2}.$$

The negative sign is used because v_2 and v_3 are in opposition.

Thus we get

$$V = I\frac{I}{R\pi}(n_r - n_s \sin.\theta)\sqrt{(n_s N_1 \cos.\theta)^2 + \left[n_r\left(N - \frac{N_1{}^2}{N}\right) - n_s N \sin.\theta\right]^2}.$$

Whence the current drawn from the mains for a given voltage V will be

$$I = \frac{V}{\frac{I}{\pi R}(n_r - n_s \sin.\theta)\sqrt{(n_s N_1 \cos.\theta)^2 + \left[n_r\left(N - \frac{N_1{}^2}{N}\right) - n_s N \sin.\theta\right]^2}}.$$

It will be seen that the value of this current will be rather high at starting; it then rises to a maximum, and finally tends towards zero when N_1 tends towards ∞. By choosing appropriate values for θ, n_r, and n_s, this maximum can be avoided and a current, and hence a torque, obtained which will decrease continuously, as would be the case with an ordinary series motor.

The torque, as we shall show, is proportional to I^2.

Power Factor.—We have seen that the electromotive force v_1 is alone in phase with I. We have

$$\cos . \phi = \frac{v_1}{V} = \frac{n_s N_1 \cos . \theta}{\sqrt{(n_s N . \cos . \theta)^2 + \left[n_r\left(N - \frac{N_1^2}{N}\right) - n_s N \sin . \theta\right]^2}},$$

or, again,

$$\tan . \phi = \frac{v_3 - v_2}{v_1} = \frac{n_r\left(N - \frac{N_1^2}{N}\right) - n_s N \sin . \theta}{N_1 n_s \cos . \theta}.$$

It will be clear from this expression that ϕ falls to zero for a certain value of the speed, and then becomes negative.

At synchronism, $N_1 = N$, and

$$\tan \phi = \tan \theta.$$

If θ is positive, that is, if the brushes are set behind the neutral line as regards the direction of rotation, the motor at synchronism *will feed watless current to the mains.*

Torque.—The torque is given by

$$2\pi c N_1 = v_1 I,$$

whence $$c = \frac{I}{R}(n_r - n_s \sin . \theta)\frac{n_s}{2\pi^2} \cos . \theta I^2.$$

It will be seen that the torque is proportional to the square of the current, and by substituting for I in the above equation the value given above, an expression may be obtained giving the value of the torque in terms of N_1, the speed.

Commutation.—On starting, there will be no sparking under brushes *a*, *b*, because of the short-circuit current *e*, *d*, which counteracts any flux along *a*, *b*. Brushes *c*, *d*, are under the influence of the flux *a*, *b*, and consequently working under the same conditions as the brushes of an ordinary single-phase series motor.

When the motor is running, from equation α it will be seen that commutation is always perfect for brushes *a* and *b*, but brushes *c* and *d* behave as though the motor were of the ordinary repulsion type, and commutation will only be perfect at synchronism.

THE SINGLE-PHASE SERIES COMMUTATOR MOTOR.

Preliminary Remarks on Compensated Series Motors in General.—Let us consider an armature through which flows a current I (Fig. 35), and we will assume that the brush lies exactly over one segment. During commutation, coil 1 of the armature takes the place of coil 2. Calling Φ_1 the total flux through coil 1, and Φ_2 the total flux through coil 2, then it is

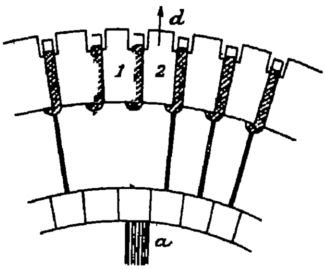

FIG. 35.—Compensated series motor armature.

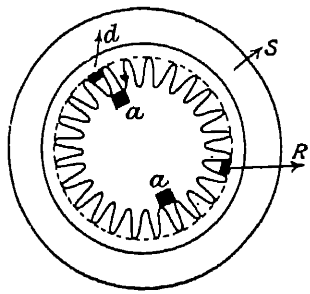

FIG. 36.—Direct-current armature rotating in magnetic ring.

evident that if $\Phi_1 = \Phi_2$ the passage from coil 1 to coil 2 will not give rise to any particular induction phenomena, and commutation will be perfect (see Commutation, Chapter II.).

If *h* is the magnetic field in tooth *d* between coils 1 and 2, then

$$\Phi_1 - \Phi_2 = h \times \Delta S,$$

where ΔS is the tooth section. Hence, in order to obtain $\Phi_1 = \Phi_2$, we must have $h = 0$.

The condition for good commutation is, that the flux should be zero in the tooth between coils passing out of, and into commutation.

Let us take the case of a direct-current armature (Fig. 36) rotating in a magnetic ring S. When a current flows through

the armature, the flux in the tooth, *d*, increases as the current increases. To obtain a flux in the tooth *d* that will be equal to zero, it is necessary to wind on to S a similar winding to that of the armature, the magnetic axis of which will coincide with that of the armature.

By allowing the armature current to flow through this winding, it will be possible to obtain a flux equal to zero in the tooth. By placing on S a second winding such as will give a flux perpendicular to the brushes *aa*, we have now got a series direct-current motor with compensation, such as that shown in Fig. 37. Obviously, for such a motor, commutation will be practically perfect at all speeds.

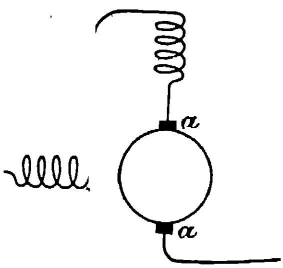

FIG. 37.—Compensated motor.

If such a motor is supplied with alternating current, we may consider the following points:—

(a) **Power Factor.**—If we assume perfect compensation for the rotor flux, no wattless E.M.F. can be induced in the rotor, and the alternating current flowing through the motor will only induce an E.M.F. E in phase opposition with the current. On account of the inherent self-induction of the stator, on the other hand, a wattless E.M.F. will be induced in it, E′, in quadrature with the current. If ϕ represents the angle between the current and the E.M.F. at the motor terminals, then $\tan \phi = \frac{E'}{E}$.

How will the power factor vary according to the number of poles chosen for a given motor speed and rotor diameter? Many authors have stated that the power factor would increase with the number of poles, but this is an erroneous statement.

If, whatever the number of poles, we maintain the same number of conductors on the rotor, so as to always have a series winding, then, for the same flux value in the air gap, the induced E.M.F. E must retain the same value whatever the number of poles may be.

Assuming now that the various poles are all connected in series, the wattless E.M.F. E′ will also remain the same. This

may be understood from the following remarks. By increasing the number of poles we do, in fact, decrease the section of each one of them, and, therefore, the self-induction coefficient of their excitation circuit; but since, on the other hand, their number has been increased, E′ remains unchanged, and $\tan\phi = \frac{E'}{E}$ also remains unaltered.

From the point of view of the power factor, therefore, there is no advantage in increasing or decreasing the number of poles, and the only advantage of a large number of poles will be to reduce the bulk of the lateral rotor connections.

(b) **Commutation.**—The presence of an alternating current will cause a certain amount of trouble because of the phenomenon of static induction which is due to the alternating field. Much of this trouble may be eliminated by using coils with only one turn, so as to keep the short-circuit current under the brushes to a low value, and by providing resistant connections between the armature and the commutator segments (see Chapter II.). A further method, due to Latour, consists in providing an auxiliary field, acting on the coils under commutation, and capable of inducing an equivalent E.M.F. dynamically.

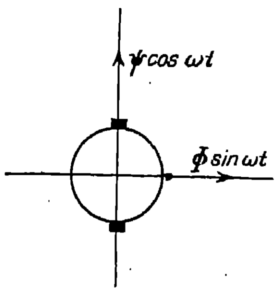

FIG. 38.—Motor flux and induced E.M.F.

Turning to Fig. 38, if $\phi \sin \omega t$ is the motor flux, then the E.M.F. e^1 induced in the short-circuited sections is proportional to

$$\omega\phi \cos \omega t.$$

Let us consider an auxiliary flux $\psi \cos . \omega t$ in the direction of the brushes *aa*. In order to counteract e^1 by an equivalent E.M.F. e^2 dynamically induced, we must develop a flux which will of course depend on the speed.

It is only necessary to create such a flux just over the short-circuited sections, and this can be done by auxiliary coils, connected in parallel to the motor terminals, and covering only a very few stator slots.

(c) **Efficiency.**—In order to obtain the same torque with an alternating current as with a direct current, the effective value of the alternating current must be equal to the value of the direct current. The maximum flux in the motor will therefore be $\sqrt{2}$ times greater than the flux produced in the case of direct current.

Moreover, the stator will be the seat of variable magnetisation.

It will be appreciated from this that the losses will be considerably higher, and for equal ratings the motor would heat unduly.

The same motor will consequently have to be rated lower than would be the case for a direct-current machine.

Characteristics Common to all Single-phase Commutator Motors.—It will now be apparent that all we have said concerning the repulsion motor can apply to the single-phase series motor, the former being in reality only a form of the latter.

To obtain a clearer idea of the principle of the series motor, let us consider the case of an ordinary shunt or series direct-current motor. Here the direction of rotation will remain the same if we reverse the direction of the applied electromotive force, since the current in the armature and field circuits both reverse. Provided, therefore, that the magnetic circuit is laminated, an ordinary series or shunt direct-current motor can be operated on an alternating E.M.F.

The various circuits of the motor can be connected to each other directly, in shunt or series, or inductively, by means of an auxiliary transformer, or the transformer being the motor itself, which gives us the repulsion motor. It is the inherent properties of the alternating current that gives the alternating current commutator motor a far greater variety of connections than possessed by the direct-current motor.

But there is a fundamental difference between the alternating-current motor and the direct-current motor. Whereas in the latter, voltage is absorbed by a counter electromotive force and by resistance, representing output, and power loss, in the former we must take into account a new factor, inductance: the voltage absorbed in this case will be wattless, and will cause a lowering of the power factor. In the direct-current

motor, designers aim at a strong field combined with a relatively weak armature, so as to reduce armature reaction as far as possible.

But in the alternating-current motor a good power factor is an essential consideration, and good design will entail low self-inductance, the combination of a strong armature and a weak field, and consequently some method must be devised to eliminate the effects of high armature reaction.

It becomes necessary, then, to reduce the magnetic flux of armature reaction, or to increase the effective magnetic reluctance, and this is accomplished by the various forms of compensation described.

Every single-phase commutator motor thus consists of a field winding, an armature winding, and a compensating winding.

The compensating winding may be connected in series (but in reversed direction) with the armature winding, or it may be short-circuited upon itself, acting as a short-circuited secondary, inductively, with the armature as primary, or it may be energised by the supply current, and the armature short-circuited as secondary.

Thus we get the conductively compensated series motor, the inductively compensated series motor, and the repulsion motor.

The compensating winding fulfils a double purpose; it reduces the armature self-inductance to that of the leakage flux, and it neutralises the armature reactance, which, as we have seen, permits the use of very high armature ampere turns.

The field winding should produce the maximum magnetic flux with the minimum number of turns, and this means that as large a magnetic section as possible should be obtained, particularly at the air-gap. The compensating winding should be as close to the armature winding as possible.

Calling A the armature winding, C the compensating winding, and F the field winding, the various types of single-phase commutator motors may be classified as follows (Steinmetz) :—

In all these types of motors, all three circuits are connected in series with each other either inductively or directly, and therefore they all have the same general characteristics as the direct-current series motor.

Primary.	Secondary.	
A + F	—	Series motor.
A + C + F	—	Conductively compensated.
A + F	C	Inductively compensated.
A	C + F	Inverted repulsion or inductively compensated series motor with secondary excitation.
C + F	A	Repulsion motor.
C	A + F	Repulsion motor with secondary excitation.
A + F, C	—	Series repulsion motors.
A, C + F	—	,, ,, ,,

In the conductively compensated types, by a suitable choice of the ratio of turns, over-compensation, complete compensation, or under-compensation can be obtained. In all other types, armature and compensating windings are in inductive relation, and compensation will be practically complete.

Under-compensation leads to sparking, but over-compensation is used in some types of motors to overcome local under-compensated armature reaction at the brushes, but this method is undesirable, as it leads to a lowering of the power factor through the self-inductive flux of over-compensation.

In the first compensated single-phase commutator motors, the field and compensating windings were massed together in a single coil; repulsion motors were usually built with field and compensating coils combined in a single distributed winding.

Eickmeyer introduced a type of series motor with a separate massed field and distributed compensating coils, and this method is now always employed in the case of reversible motors.

Series motors certainly give the best power factor, but, on the other hand, commutation is fairly poor, and for motors of any size commutating poles and resistant connections must be used.

Inductive compensation is preferable where it can be used; its advantage lies in the fact that the winding, being independent of the mains, can be made for very low voltage, which results in an economy of space and insulation.

Repulsion motors, characterised by a lagging quadrature flux, which transfers the power from the compensating winding to the armature, have much better commutation. This,

moreover, improves rapidly with increasing speed, and, as we have shown, becomes perfect near synchronism.

It is possible to combine in a single machine the advantages of the series motor and the repulsion motor. Such a machine has two lines of brushes at right angles to one another, and is known as the Latour motor, which has been described earlier in this chapter.

The line of brushes, A, will be in series with the stator winding, and the other, B, short-circuited.

When line A coincides with the poles, and therefore B coincides with the neutral line, the torque will obviously be equal to zero, for it is equal to zero in this case for both the series and repulsion motors.

If A coincides with the neutral line, and B with the poles, the motor will run like a series compensated motor. The line of brushes that is coincident with the poles short-circuits the rotor for that component of the electromotive force which we have called static, and therefore the same armature winding will act in two ways, as the armature of an ordinary series motor, and as a short-circuited compensating device, thus eliminating all necessity for installing a separate compensating winding.

For any other position of the brushes the operation is more complicated, the motor running partly as a repulsion, partly as a series machine, and the resultant torque is equal to the combination of the torques that would be produced should the motor run either as a series or a repulsion motor.

Summary of Properties of Various Types.

To sum up the various types of motors, let E_0, I_0, Z_0 = impressed voltage, current, and self-inductive impedance of the magnetising or exciter circuit of stator (field coils) reduced to the rotor energy circuit (or circuit at right angles to I_0).

E_1, I_1, Z_1 = impressed voltage, current, and self-inductive impedance of the rotor energy circuit.

E_2, I_2, Z_2 = impressed voltage, current, and self-inductive impedance of the stator compensating winding reduced to the rotor circuit by the ratio of effective turns, c_2.

E_3, I_3, Z_3 = impressed voltage, current, and self-inductive impedance of the exciting circuit of the rotor or circuit parallel to I_0.

I_4, Z_4 = current and self-inductive impedance of the short-circuit under the brushes I_1, reduced to the rotor circuit.

I_5, Z_5 = current and self-inductive impedance of the short-circuit under the brushes I_3 reduced to the rotor circuit.

Z = mutual impedance of field excitation, that is, in the direction of I_0, I_3, I_4.

Z' = mutual impedance of armature reaction, that is, in the direction of I_1, I_2, I_5.

Let S = speed, as fraction of synchronism.

The general equations which apply to any alternating current circuit revolving with speed S through a magnetic field energised by alternating-current circuits give, for the six circuits of the general single-phase commutator motor, the six equations (Steinmetz) :—

$$\begin{aligned}
E_0 &= Z_0 I_0 + Z(I_0 + I_3 - I_4).\\
E_1 &= Z_1 I_1 + Z'(I_1 + I_5 - I_2) - jSZ(I_0 + I_3 - I_4).\\
E_2 &= Z_2 I_2 + Z'(I_2 - I_1 - I_5).\\
E_3 &= Z_1 I_3 + Z(I_3 + I_0 - I_4) - jSZ(I_2 - I_1 - I_5).\\
0 &= Z_4 I_4 + Z(I_4 - I_0 - I_3) - jSZ(I_1 + I_5 - I_2).\\
0 &= Z_5 I_5 + Z'(I_5 + I_1 - I_2) - jSZ(I_0 + I_3 - I_4).
\end{aligned}$$

These six equations contain ten variables—

$$I_0,\ I_1,\ I_2,\ I_3,\ I_4,\ I_5,\ E_0,\ E_1,\ E_2,\ E_3,$$

and so leave four independent variables, that is, four conditions which may be chosen (see table, page 64).

Various Types of Single-phase Commutator Motors.

A great number of different types of commutator motors has been designed in which the properties of the induction motor and the commutator motor are combined. In a later chapter we will deal with combined induction and commutator motors where the object in view is power factor improvement, or high starting torque; but in the present chapter it is proposed to describe briefly some of the older forms of these motors, a few of which are of considerable interest.

TABLE SHOWING COMBINATIONS OF THE FOUR VARIABLES OF STEINMETZ'S EQUATIONS.

See Fig. 41, No.	Type of motor considered.	e.	e_1.	e_2.	I_0.	I_2.	I_3.	E_1.	E_2.
7	Series motor . . .	$C_0E_0 + E_1$	—	—	C_0I_1	O	O	—	—
8	Conductively compensated series motor (Eickmeyer) .	$C_0E_0 + E_1 + C_2E_2$	—	—	C_0I_1	C_2I_1	O	—	—
23	Inductively compensated series motor (Eickmeyer) .	$C_0E_0 + E_1$	—	—	C_0I_1	—	O	—	O
Reverse of 3	Inverted repulsion or series with secondary excitation .	E_1	—	—	$\frac{C_0}{C_2} I_2$	—	O	—	$-\frac{C_0E_0}{C_2}$
3	Repulsion motor, compensated	$C_0E_0 + C_2E_2$	—	—	$\frac{C_0}{C_2} I_2$	—	O	$-$ O	—
9	Repulsion motor with secondary excitation . . .	C_2E_2	—	—	C_0I_1	—	O	$-C_0E_0$	—
24	Series repulsion motor with secondary excitation . .	—	$C_0E_0 + E_1$	E_2	C_0I_1	—	O	—	—
25	Series repulsion motor with primary excitation (Alexandersen)	—	E_1	$C_0E_0 + C_2E_2$	$\frac{C_0}{C_2} I_2$	—	O	—	—
4	Compensated repulsion motor (Latour)	$C_2E_2 + C_3E_3$	—	—	O	$\frac{C_2}{C_3} I_3$	—	O	—
11	Compensated shunt motor .	$C_2E_2 = C_3E_3$	—	—	O	—	—	O	$\frac{C_3}{C_2} E_3$

The Wagner Motor.—About the year 1897 the Wagner Electric Company, of St. Louis, in America, entered upon the manufacture of single-phase commutator motors (see also p. 68).

The machine starts up on the repulsion principle Carbon brushes, cross-connected, bear upon a commutator, and a high starting torque is consequently developed.

When the motor has attained full speed, the commutator segments are all connected together by means of an automatic centrifugal device, and the rotor winding is thus transformed into a short-circuited winding, and the motor runs as an induction motor. The brushes are simultaneously removed from contact with the commutator. If the power supply should fail, the motor circuits are automatically restored to starting conditions. A commutator with a vertical face was employed.

The Schüler Motor.—This motor is similar to the Wagner motor in that it is started as a repulsion motor and afterwards run as an induction motor. But it differs from the former in that resistances are inserted in the rotor circuits at starting and are gradually cut out.

At the moment of starting there are relatively very considerable resistances external to the slip-rings, and the motor is practically operating as a repulsion motor. These resistances are gradually cut out until finally the motor is practically an induction motor with its rotor windings short-circuited.

The Déri Variable-pole Repulsion Induction Single-phase Motor.—Déri has designed and built single-phase motors in which, by simply varying the connection of the stator windings, the motor is changed from a repulsion to an induction motor (British Patent No. 2426 of 1898).

Let us consider a 30-conductor bipolar armature winding (Fig. 39). The winding (Fig. 40) with $(2 \times 30) = 60$ conductors may be considered to be derived from Fig. 39 by splitting each of the thirty conductors and spreading them out into thirty loops, the pitch of each loop being one-sixth of the circumference; consequently they form a suitable short-circuited winding for the rotor of a six-pole induction motor.

The commutator carries two sets of brushes which are short-circuited, and the motor is started as a repulsion motor by employing the bipolar stator winding. At a speed

approaching full speed, the stator connections are changed over to provide six poles. As soon as this is done, the rotor currents will find suitable paths in the short-circuited loops, and will no longer flow through the commutator and brushes.

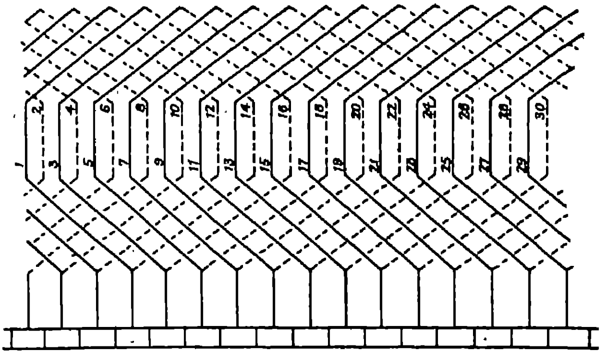

FIG. 39.—Déri variable pole windings.

Of course, the stator may be provided with two separate windings, one giving two and one six poles, or a single winding may be used alternatively by means of suitable connections.

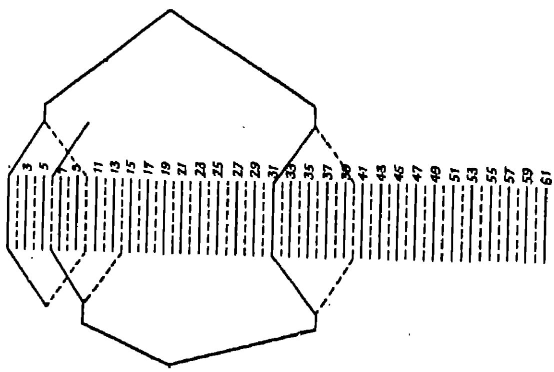

FIG. 40.—Déri variable pole windings.

Wightman Motor (Fig. 41, No. 11).—This motor differs essentially from the Latour-Winter-Eichberg motor in that the brushes whose axis is perpendicular to the axis of the stator winding constitute part of a circuit in parallel with the stator winding. Latour and Fynn (Fig. 41, No. 12) added a transformer through which the rotor circuit perpendicular to the stator axis was supplied,

Fynn's Patents.—A number of modifications were introduced by Fynn, and are shown in Nos. 13 and 14 in Fig. 41, the object of which was to vary the speed by varying the pressure at the terminals. None of these motors are at all fundamentally different from the main types already described, and are merely mentioned for their historical interest.

Punga's Modifications (Fig. 41, Nos. 15-20).—Denoting by S_a the number of turns in the armature winding in series between the bushes, and by S_s the number in the auxiliary winding on the stator, and furthermore denoting the ratio $\frac{S_a}{S_s}$ by a, then, as a rough approximation the speed of the motor in No. 15, Fig. 41, is $\sqrt{1 + a}$ times greater than synchronism. In this expression a is to be taken as positive when the M.M.F. of the auxiliary winding acts in the same direction to that of the armature winding. If the coil is so wound as to increase the speed of the motor, it will also tend to decrease the angle of lag of the primary current behind the E.M.F. The arrangement shown in No. 16, Fig. 41, gives the same results as that of No. 15. The auxiliary is now in the x axis, and therefore connected to the brushes in the x axis. The speed is calculated in the same manner as for No. 15.

No. 17 shows how Nos. 15 and 16 may be combined to obtain a greater effect (Patent 10,589). Punga also shows in his patent, ways in which his methods may be combined with the method of improving the power factor due to Latour and Fynn. This is shown in Nos. 18 and 19 on the chart, where coils E and F are the stator coils for improving the power factor, and S and H are the stator coils for obtaining speed variations.

Creedy's Patents.—The chief additional principle disclosed by Creedy is that the speed may also be varied by inserting inductance or capacity in series with that rotor circuit which is perpendicular to the stator axis, since this alters the magnitude of the cross flux. Two arrangements are shown, Nos. 21 and 22.

Modern types of single-phase commutator motors retain precisely the same basic principles as the older forms. Construction has improved, and the motors have been generally modernised in form, and have acquired great compactness and reliability.

In a later chapter dealing with the practical application of these motors, several types will be more fully described, while a separate chapter is devoted entirely to traction motors.

By way of comparison with the early types described in this chapter, we should mention a few modern developments, the first of which, by the Wagner Company, is a direct descendant of the 1897 Wagner motor just described.

The Wagner Repulsion Induction Motor, BA Type.—This motor operates on exactly the same principle as the first single-phase motor placed on the market in 1897. As a repulsion motor, it has the heavy starting torque, characteristics of the well-known series type of motor, and as an induction motor, the ability to carry a load, once started, at an approximately constant speed.

Some idea of the relation of starting torque to starting current can be obtained from the fact that, at the instant of starting, the motor, if thrown directly across the line, takes from two to three times full-load current and develops from two to three times full-load torque, depending on the brush-setting and the size of the motor.

The large starting torque quickly brings the motor up to speed, and therefore produces a minimum line disturbance.

The starting current may, if necessary, be reduced by the use of a starting resistance.

With a starting current of one and a quarter times full-load current, the motor develops a starting torque equal to the full-load torque.

By shifting the brushes the starting characteristics of the motor may be varied so that it will deliver an extra heavy torque at starting as is required when used for driving machines having a heavy flywheel effect, or so that it will exert an extra heavy torque when the machine nears normal speed, as is required in the operation of such applications as centrifugal pumps, blowers, etc.

The centrifugal device used automatically to lift the brushes from the commutator and to short-circuit the commutator bars when the motor approaches its running speed is very rugged, and although this might appear at first sight a complication and a possible source of breakdown, very little trouble seems to occur with this apparatus.

These motors are built in either horizontal or vertical shaft types for all standard voltages and frequencies in sizes from $\frac{1}{12}$ to 50 h.p.

Fynn-Weichsel Motor.—This type was developed by the Wagner Electric Corporation, but it is essentially a constant-speed motor designed with a view to improving the power factor. As such it falls, together with a number of similar commutator machines, under the heading of compensated induction motors, and will be dealt with in a later chapter.

Losses in Resistance Connection in Single-phase Commutator Motors.—We will conclude this chapter on single-phase commutator machines by some remarks on resistance connectors, which have been already mentioned in the chapter on commutation.*

By the use of such resistant connectors a greater magnetic flux per pole may be used, and since the size of the motor that can be worked successfully at a given frequency and speed depends on this, whatever the disadvantages of connectors may be, it is desirable in many cases to embody them in the design.

Let i_e be the value of the eddy-current in a resistant connector caused by the transformer action between the existing coil as primary and the armature coil as secondary, and v_e the voltage. Then

$$i_e = k_1 \frac{v_e}{r}$$

where r is the resistance of a connector and k_1 a constant.

The losses in the connector will be

$$i_e^2 r = k_1^2 \frac{v_e^2}{r}.$$

If we denote the load current in the armature by i_a, the loss due to the load current in the connectors will be

$$k_2^2 i_a^2 r.$$

The total loss will be

$$k_1^2 \frac{v_e^2}{r} + k_2^2 i_a^2 r.$$

Differentiating this equation, and equating to nought, will give us a value of r for minimum loss,

$$r = \frac{k_1}{k_2} \frac{v_e}{i_a}.$$

* *The Journal of the Manchester Municipal College of Technology*, 1926.

Filling in this value in the above expression we have

$$\text{Total losses} = k_1 k_2 i_a v_e + k_1 k_2 i_a v_e,$$

from which we see that the value of r, which gives the minimum loss, is the one which makes the eddy current loss equal to the loss due to load current.

The constants k_1 and k_2 depend on the inductance in the short-circuited coils, and the width of the brush respectively.

It is common practice in single-phase motors to make the width of the brushes about equal to the width of two commutator strips, or a little less.

Taking an example, the 409B Westinghouse single-phase 6-pole traction motor of 145 h.p. has an armature with 42 slots, 12 conductors per slot, with resistant connectors to 252 commutator bars, each ·022 of an ohm. The full-load current is 500 amperes at 275 volts.

Although the width of the brush is almost equal to the width of two commutator strips, so that three connectors are in parallel, the resistance is not actually reduced to $\frac{1}{3}$, because the contact drops between the incoming and outgoing commutator strips and the brush cut down the current. The effect is to make the current in each connector about ·4 of the current.

The losses in the connector due to load current are equal to that produced by an alternating current having a maximum value of $\frac{500 \times 1{\cdot}41 \times 0{\cdot}4}{3} = 94$ amperes.

That is to say, $66{\cdot}6 \times 66{\cdot}6 \times 0{\cdot}22$ watts $= 96$ watts. There is the equivalent of $2\frac{1}{2}$ connectors in parallel, and the losses occur at six brush arms. Thus we have

$$96 \times 2{\cdot}5 \times 6 = 1440 \text{ watts.}$$

Taking the load current $i_a = 500$, the value of k_2 works out to $0{\cdot}51$.

The method of arriving at the value of the coefficient k_1 is to first of all deduct a suitable amount from the transformer voltage to allow for the drop in the brushes (about three volts for each contact drop is not far wrong in practice) and thus arrive at the voltage v_e available for driving the eddy-current. The next step is to find an approximate allowance for the effect

of inductance in reducing the effective current in the short-circuit path. This is best done by plotting curves and arriving at an approximate average wave-form for the eddy-current. The effect of inductance is, of course, dependent on the speed of the motor.

At the speed 800 r.p.m. in the case considered, the heating value of the current is somewhat less than 80 amperes (taken as passing in three connectors), so that the total heating caused by the eddy current is about $80 \times 80 \times \cdot 022 \times 3 \times 6 = 2300$ watts. Equating this to the expression $k_1{}^2\frac{v_e{}^2}{r}$, we find that $k_1 = 0{\cdot}71$.

Thus, the theoretically best value for r to give the smallest loss on the whole would be $r = \frac{\cdot 71 \times 10}{\cdot 51 \times 500} = \cdot 028$ ohm per connector.

It does not necessarily follow that a designer will choose the connector that gives the sum of the losses exactly at its minimum. A considerable departure may be made without any serious increase in the total losses.

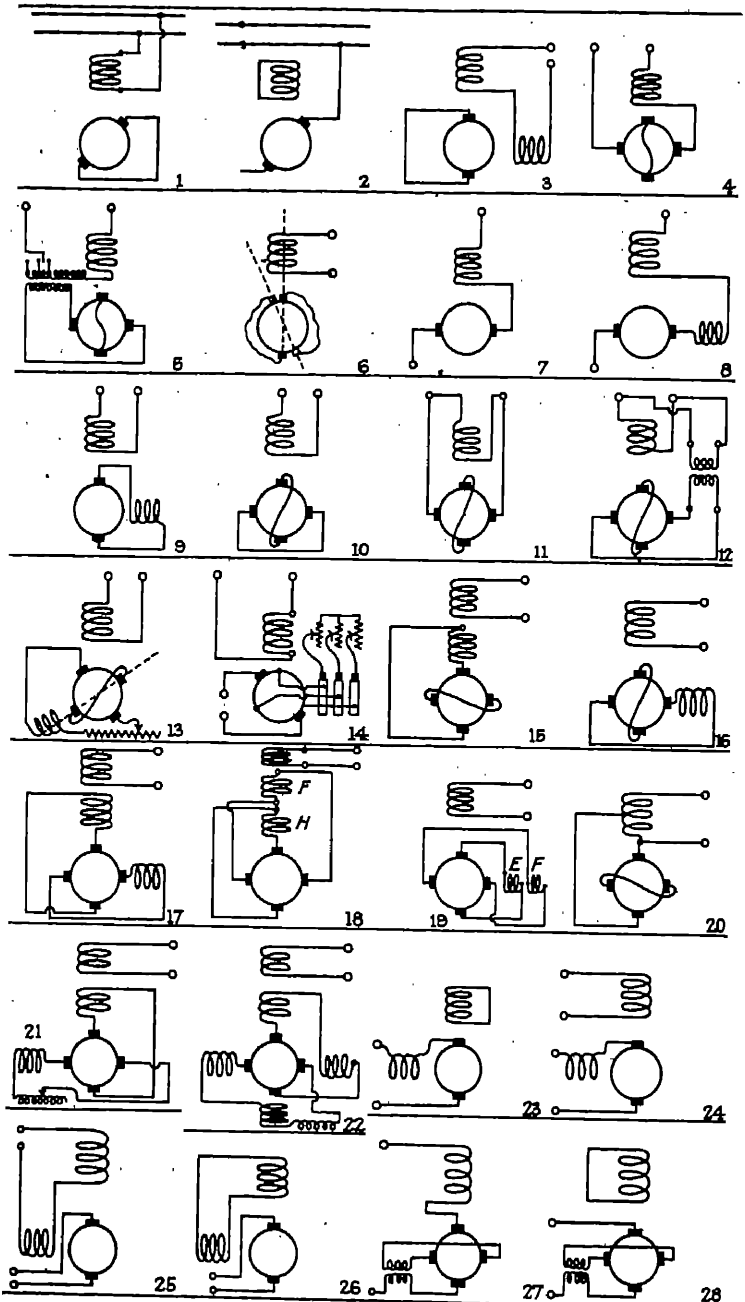

FIG. 41.—Chart showing various types of single-phase commutator motors.

1. Repulsion motor.
2. Inverted repulsion motor.
3. Atkinson or compensated repulsion motor.
4. Compensated Latour-Winter-Eichberg repulsion motor.
5. Same as 4, with variable ratio transformer.
6. Déri motor.
7. Series single-phase motor.
8. Series neutralised single-phase motor.
9. Induced series motor (see also 3).
10. Atkinson single-phase shunt motor.
11. Wightman's 1888 single-phase shunt motor.
12. Latour's 1903 single-phase shunt motor.
13. Fynn's 1905 single-phase shunt motor.
14. Fynn's 1902 single-phase shunt induction commutator motor.
15. Punga's motor, connections for varying pressure across armature.
16. Punga's motor, connections for varying pressure across field.
17. Punga's motor, connections for varying pressure across armature and field.
18. Punga's motor, with the addition of a winding for improving the power factor on that of Fig. 15.
19. Punga's motor with the addition of a winding for improving the power factor on that of Fig. 16.
20. Punga's alternative connections for varying the pressure across the armature.
21. Connections of Creedy's variable-speed, single-phase motor.
22. Alternative connections of Creedy's single-phase motor.
23. Inductively compensated series motor.
24. Series repulsion motor with secondary excitation.
25. Alexandersen series repulsion motor with primary excitation.
26. Compensated inverted repulsion motor, or inductively compensated series motor, with secondary excitation.
27. Rotor-excited series motor with conductive compensation.
28. Rotor-excited series motor with inductive compensation.

CHAPTER IV.

THE POLYPHASE COMMUTATOR MOTOR.

A FULL analytical treatment of the single-phase commutator motor naturally covers the polyphase motor as well. There is little more to add as regards the theory of these motors, and it will be the object of this chapter, while studying the characteristics of the three-phase motor, to leave, as far as possible, analytical methods aside and explain as simply as possible what actually takes place in a machine of this kind.

The single-phase machine, as will be seen from the second part of this volume, has found many applications. But it has more particularly held its own where the use of a single phase was in itself a considerable advantage. This would, of course, be the case wherever the question of current collection arises, such as gantry cranes, or, more important still, traction. Elsewhere the three-phase motor has gradually come to the fore, evenly loaded phases being the principal advantage. Clearly, no motor that could not be directly connected to a three-phase supply system could ever have been generally useful industrially, and the advent of the three-phase commutator motor marked a new era for these machines. They are built for all ratings, from fractional horse-power to some 800 h.p. Larger powers are usually provided for by cascaded sets, which will be more fully dealt with in later chapters.

The three-phase motor, like the single-phase machine, may be used with a rotor-stator transformer, and for the larger ratings this is almost invariably the case. By these means the motor may be direct connected to high-tension mains, while the voltage on the rotor is kept within reasonable limits in order to ensure satisfactory commutation. Alternative methods of transformer connection are shown in Fig. 42. The trans-

former serves, as we shall see, a double purpose : besides lowering the voltage on the rotor, it allows phase multiplication.

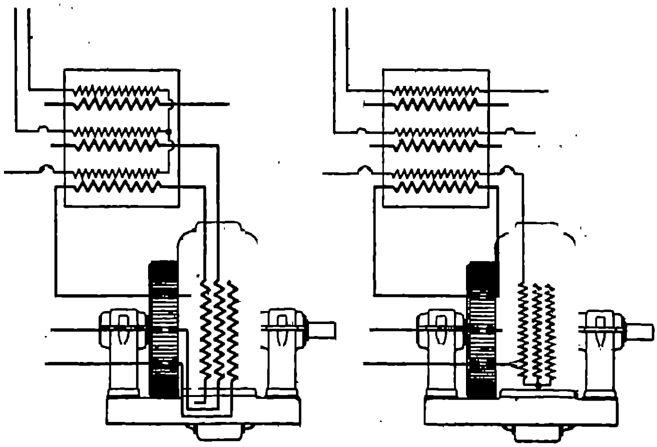

FIG. 42.—Alternative methods of transformer connections.

Let us consider a Gramme ring, such as that shown in Fig. 43, at rest, provided with three brushes set at 120°.

If we feed the brushes from a three-phase supply we will

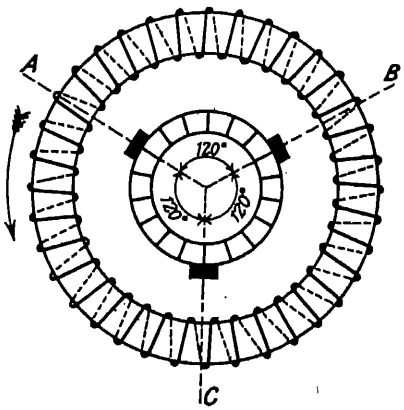

FIG. 43.—Diagram of Gramme ring with three brushes.

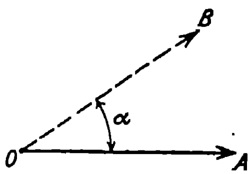

FIG. 44.—Rotating fields in Gramme ring.

get a rotating field, the speed of which for a 50-cycle frequency will be 3000 r.p.m.

The rotor will have a certain self-induction due to the variable flux. Let us now assume that the field rotates counter

clockwise, and is represented by the vector OA (Fig. 44) rotating about O at a speed of 3000 r.p.m. If we shift the brushes through a certain angle α in the direction of rotation of the motor, it is clear that we also shift the position of the field through the same angle, and the vector OA will consequently lead its primitive position by the angle α. That is to say, at the time when it formerly passed through the position OA, it will now pass through OB.

If the ring is now placed in an ordinary induction motor stator, and the rotor and stator are connected in series, we will obtain two rotating fields. The stator and rotor will be so connected that the directions of rotation will be the same for both fields, OS and OR (Fig. 45), both of which rotate at a speed of 3000 r.p.m. The angle between them, β, can be adjusted at will by shifting the brushes, the effect of which will be to shift OR with regard to OS. It will be easily seen that this will give rise to a torque, due to the mutual action of one field on the other.

Let us now assume that the rotor is rotating. The speed of the rotating field will not be affected, since the brushes remain stationary. If we consider the armature turns in angle AOB, as soon as one of them passes into AOC, another passes out of BOC into AOB, so that, to all intents the turns may be considered as stationary in space. The power factor, however, will be considerably modified by the speed of rotation. When the rotor is at rest, the supply current is lagging behind the E.M.F. on account of the rotor self-induction. Each turn is traversed by a current the frequency of which is that of the mains. As the speed of rotation increases, in the same direction as that of the rotating field, this frequency will decrease, and become zero when the speed reaches 3000 r.p.m. The turns will then act as a self-induction resistance. If the speed is increased beyond this, the armature will produce wattless current and act as a condenser. From the above consideration it will be seen that the motor will have the following main characteristics :—

(1) It will have a series characteristic as has been shown for single-phase machines.

(2) At synchronism the rotor no longer has any E.M.F.

induced in it, and acts as an ohmic resistance. The resistance being small, the voltage between brushes will be practically zero.

(3) In the neighbourhood of synchronism the power factor will be near unity.

(4) Recuperative braking may be easily achieved by shifting the brushes back past neutral position, so as to alter the relative flux positions as shown (Fig. 46).

This type of motor has two important advantages :—

(1) The speed is easily variable. The speed torque characteristic may be a series characteristic, that is, the speed will vary with the load and rise to an unlimited extent at no load, or it may be a compound characteristic, that is, the speed will

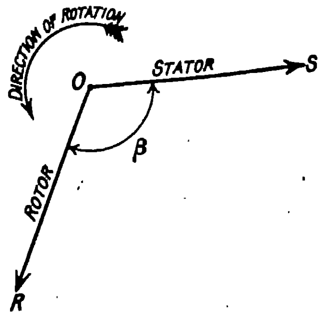

FIG. 45.—Rotating fields in Gramme ring.

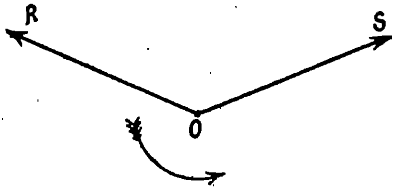

FIG. 46.—Recuperative braking.

vary with the load, but will be limited at no load. By the use of simple devices, the compounding may be varied, that is to say, the difference between the speed at normal load and the speed at no load can be adjusted at will. Similarly, the speed at no-load can be adjusted to any value, the amount of compounding being itself adjustable for each speed obtained.

The series polyphase motor would seem, however, costly and difficult to design for very high ratings (above 1000 h.p.). The combination of an induction motor in cascade with a commutator motor effectively solves this difficulty, and such a combination possesses all the advantages of a series polyphase commutator motor, and is, moreover, both efficient and economical.

Although this combination, which is perhaps the most important application of commutator motors, will be studied in detail in subsequent chapters, it is necessary to give here some idea of the principles involved.

It is well known that with an ordinary induction motor only one single speed can be obtained under no-load conditions, a speed approximating to the synchronism speed, with only a very slight variation between the speed on load and the speed on no-load. Calling N_s the synchronous speed, then, the slip s defined as

$$s = \frac{N_s - N}{N_s}$$

will be somewhere about 2 to 4 per cent. for large motors.

Now the principle of cascading an induction and commutator motor rests on the following considerations. The slip s may be increased by inserting resistances in the rotor circuit. But, for a given value of the torque, the loss through Joule effect in the rotor circuit is proportional to the slip. Thus, in the case of a 1000 h.p. motor, for instance, running at 500 r.p.m. at synchronism, the speed under normal load will be

$$500\ (1 - 0{\cdot}02) = 490 \text{ r.p.m.}$$

Assuming an efficiency of 94 per cent. and a 2 per cent. Joule loss in the rotor circuit, and should we insert resistances in order to lower the speed to 450 r.p.m., the slip will become 10 per cent. and the Joule loss will now be $20 \times \frac{0{\cdot}10}{0{\cdot}02} = 100$ h.p.

Bringing the speed down from 500 to 450 r.p.m. increases the Joule loss from 20 to 100 h.p.. The power will then be

$$6000 \times \frac{450}{490} = 920 \text{ h.p.,}$$

and the efficiency will have fallen to

$$\frac{930}{920 + 100 + 40} = 86{\cdot}7 \text{ per cent.}$$

Supposing, now, instead of inserting resistances in the rotor circuit we insert the windings of a series-wound commutator motor coupled to the same shaft, this motor will recuperate the

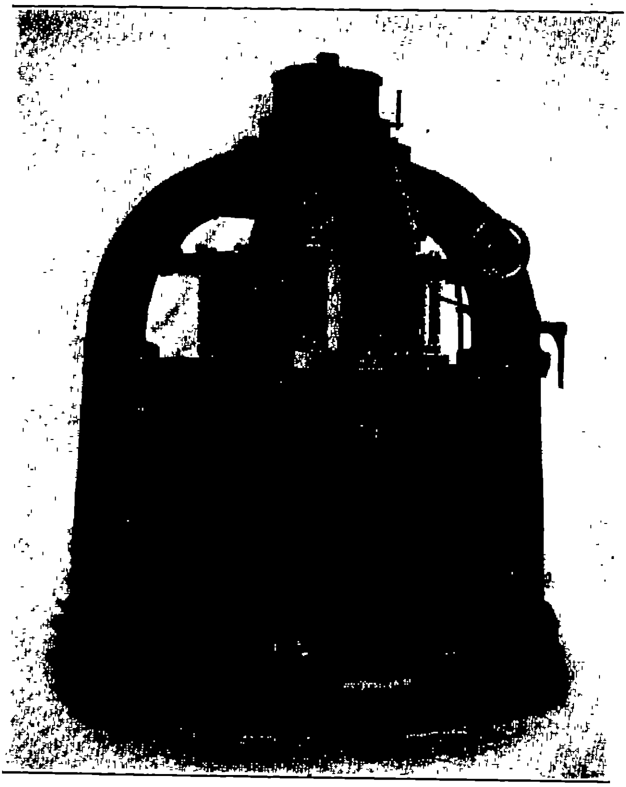

FIG. 47.—Vertical 460 h.p. motor wound for 6600 volt-supply (Jeumont).

[To face page 79.

energy that would otherwise be lost in the rotor circuit consequent on the slip.

The available power on the shaft will then be constant whatever the speed. The amount of slip, moreover, can be adjusted by shifting the commutator motor brushes. The speed of such a combination can be easily controlled.

(2) The second advantage of the series commutator motor is an extremely important one. By its very nature it is capable of providing its own excitation current. The capital importance of this point can readily be understood. Any alternating current machine requires a certain number of kilovolt-amperes for excitation purposes; these are provided by the mains, in the

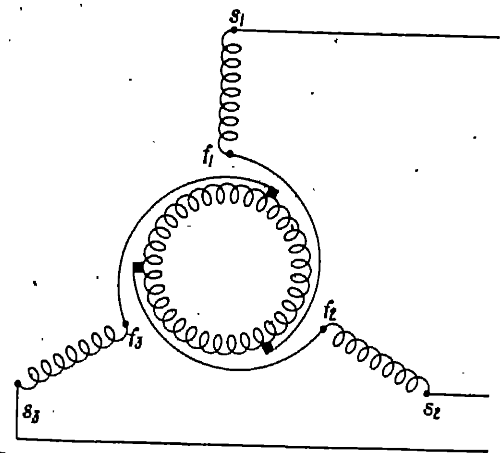

FIG. 48.—Simple diagram of commutator motor.

case of the ordinary induction motor, and consequently wattless current is drawn from the alternators. The series commutator motor, on the other hand, whether it be employed alone or in cascade with an induction motor, is self-exciting. It may even be run so as to feed back wattless energy to the mains while absorbing true watts. From these remarks the value of the commutator machine as a power factor compensator will be recognised, and this important application is dealt with in the next chapter.

The stator of the three-phase series motor is identical to that of a three-phase induction motor. The three phases, however, are not star or delta connected, but are separate, the

six ends of the three windings being brought out to six terminals —s_1, f_1, s_2, f_2, s_3, f_3—the letter s indicating the start of the winding, and the letter f the finish.

This lettering has been adopted to avoid the use of the letter i, which might lead to confusion, but start and finish are taken to mean " in " and " out."

The rotor is identical to that of an ordinary direct-current machine. In the simplest case (Fig. 48), three brushes are provided 120° apart that can be shifted together, always retaining their relative spacing. The brushes are connected to the stator windings as shown, and s_1, s_2, s_3 are connected to the mains. This simple diagram gives the clearest indication of the operation of the three-phase series motor, but in practice the windings are not quite so simple. In order to ensure good commutation the rotor is usually supplied with 6, 9, or 12 phases through a transformer, the primary of which is fed in series with the stator. The rotor has then 6, 9, or 12 lines of brushes connected to the corresponding transformer secondary terminals. The transformer, then, serves a double purpose; phase multiplication on the one hand, and on the other hand its presence lowers the voltage on the commutator.

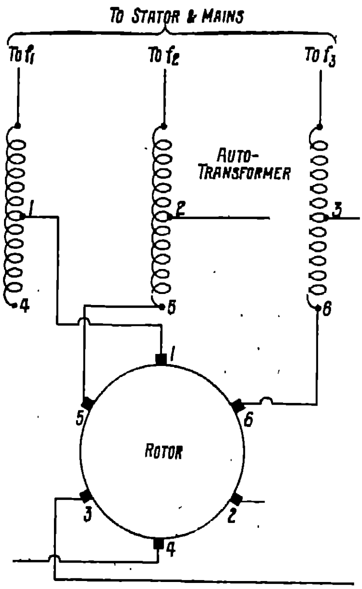

FIG. 49.—Auto-transformer for six phases.

It may be interesting to explain briefly the methods used for winding these transformers. For six-phases, an auto-transformer is usually provided, and the connections should be clear from Fig. 49, the ends of each coil of the secondary winding being connected to diametrically opposed brushes.

For nine phases, the transformer is divided into three columns, each provided with three windings. The transformer

is, moreover, wound with two separate secondaries as shown (Fig. 50). One of the secondary windings gives a triangle, the other a polygonal figure formed out of two groups of three equal sides. A study of the diagram (Fig. 51) will make the arrangement clear.

For twelve phases a transformer is used having three distinct secondary windings, two of which are closed, and the third open, with a neutral point, as shown in Fig. 52. The first two of these give us triangles, and the third a six-pointed star (Fig. 53).

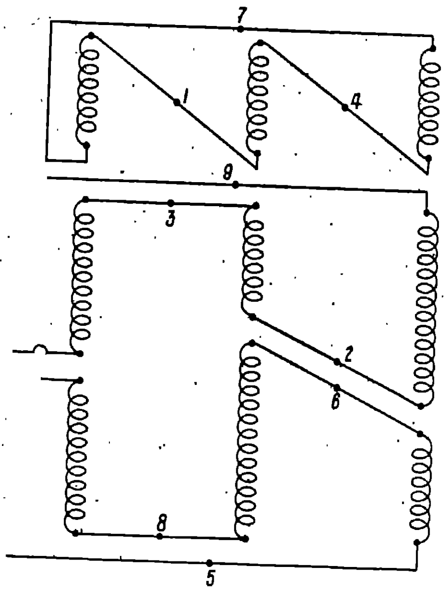

FIG. 50.—Transformer for nine phases.

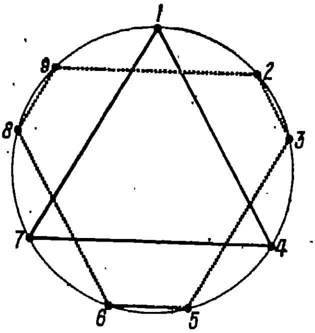

FIG. 51.—Diagram for nine phases.

The number of turns of the windings is made proportional to the length of parallel chords in the diagram. These various arrangements are those used by the Ateliers de Jeumont, but may be taken as typical.

We have, so far, only considered the connections of a two-pole machine. Where there are more than two poles, the brushes are not always evenly distributed over the commutator.

The rotor winding is a parallel winding: if we take p equidistant points on the commutator, p being the number of pairs of poles, then such points p will be equipotential points.

6

Now we know by definition that the geometrical angle 3
which one must travel through to pass once, and once only
different potentials on the commutator represents 360 elect
degrees. If k be the number of commutator segments,
one segment will cover an angle of $360p/k$ electrical deg
If the rotor is wound for q phases, then the terminals numb
1, 2, 3, . . . q will be connected to points on the commut
spaced $360/q$ electrical degrees apart. This can be don
several ways. If the commutator circumference be divided

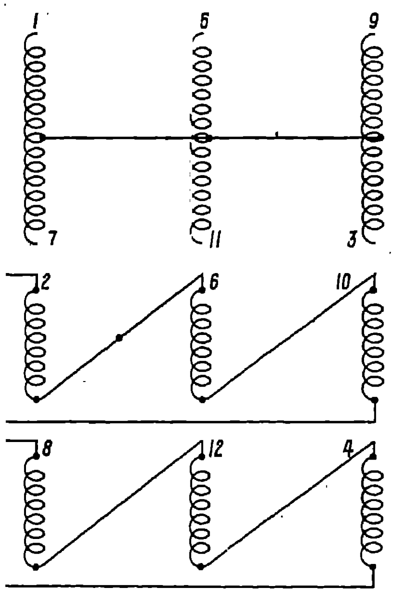

FIG. 52.—Transformer for twelve phases.

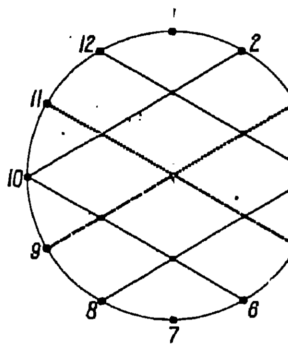

FIG. 53.—Diagram for tw phases.

p equal parts, and each of these divisions into q equal
numbered 1, 2, 3 . . . q, all points numbered 1 are pos
positions for the brushes belonging to phase 1. Several of
points may be used simultaneously in order to limit the cu
density in the brushes. We have shown (Fig. 54) the
possible combinations in the case of a three-phase eight
motor using two sets of brushes in parallel.

In other words, the brushes which must be connecte
consecutive transformer terminals are those that are electri
consecutive, and not those that are consecutive as cou

around the commutator. Two such electrically consecutive brushes are $\frac{k}{p}\left(\frac{1}{q} + n\right)$ apart where n is any positive or negative integer.

The possibility of spacing out the brushes on a commutator

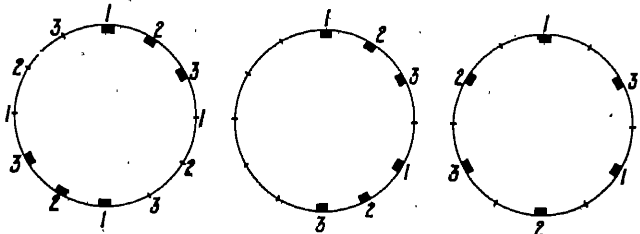

FIG. 54.—Three possible combinations of brush positions for three phase eight-pole motor.

in various ways, either grouping them together on one side of the machine, or dividing them into two diametrically opposed groups, or spreading them out evenly, is a very important one from the point of view of mechanical construction, accessibility, and the design of simple brush shifting gear.

Fundamental Principle of the Polyphase Commutator Motor.—Having now some idea of the construction and connection of the three-phase commutator motor, we may attempt to give a further simple explanation of its action and thus emphasise the fundamental difference between a commutator motor and an ordinary induction motor.

The author has tried to remove from the following explanation any mathematical considerations in the hope that it may throw some further light on the more complex theory given for the single-phase machine.

Let us consider the case of an ordinary induction motor in which the three ends, s_1, s_2, s_3 of the stator are connected to the mains; and f_1, f_2, f_3 are connected together, forming what is known as a neutral point.

The stator, so connected, will give rise to a rotating field, the speed of rotation of which, with regard to the rotor, will be the speed of synchronism, $N_s = \frac{60\omega}{p}$ where ω is the supply frequency, and p the number of pairs of poles.

Let us now consider a rotor having the same number of

poles as the stator, and $q = 6$ phases, for instance. This rotor will have six windings connected at one end to a neutral point, and at the other end to six slip-rings.

Let us close the rotor circuit by connecting the slip-rings to a six-phase resistance. Now, if the rotor rotates in the same direction as the stator field, with a speed N, the rotor winding will be swept by a field rotating with regard to the rotor at a speed,

$$N_s - N.$$

The frequency of the currents induced in the rotor winding will be $g\omega$ where g is the slip. The rotor will set up a rotating field whose speed, with regard to the rotor, will be $N_s - N$, and with regard to the stator $(N_s - N) + N = N_s$. Now, if instead of slip-rings we provide the rotor with a commutator and six rows of brushes, and let them be connected to a six-phase resistance as before, then, so long as the motor rotates at a speed N, nothing will be changed as far as torque is concerned, but there is a fundamental difference due to the presence of a commutator. The frequency of the induced currents circulating through the resistances is no longer $g\omega$, but the actual frequency of the mains, a fact which is due to the well-known property of the commutator as a frequency changer. We can now alter the connections and suppress the neutral point f_1, f_2, f_3, connecting these points of the stator winding to the brushes by means of a six-phase transformer. The stator and rotor are now in series. The frequency in the stator is still the frequency of the supply system; but the machine, when so connected, has entirely new characteristics.

In the ordinary induction motor, at synchronism, no E.M.F. is induced in the rotor and the torque on the shaft falls to zero. In the present case, the E.M.F. induced in the rotor is still equal to zero at synchronism, but current still flows through the rotor because it is in series with the stator. The torque, which results from the mutual action of the stator and rotor currents, therefore exists. Above synchronism, the rotor field rotates in the opposite direction at a speed $N - N_s$ with regard to the rotor, therefore with a speed N_s with regard to the stator, and a torque still exists.

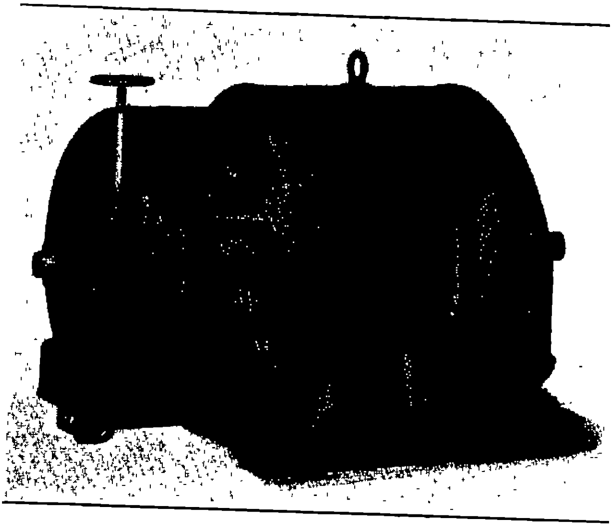

FIG. 55.—Small three-phase motor by Brown, Boveri & Co., Ltd., Baden.

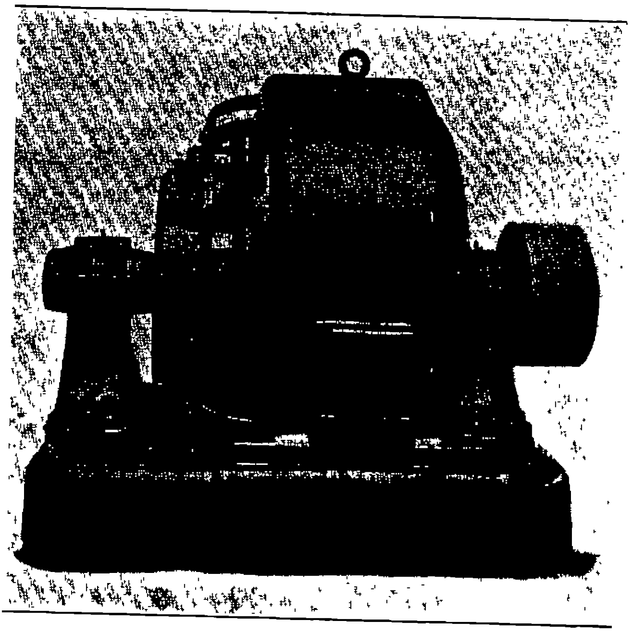

FIG. 56.—Motor for driving mine fans, 450 h.p., wound for 3100 volts, 480/230 r.p.m. (Jeumont).

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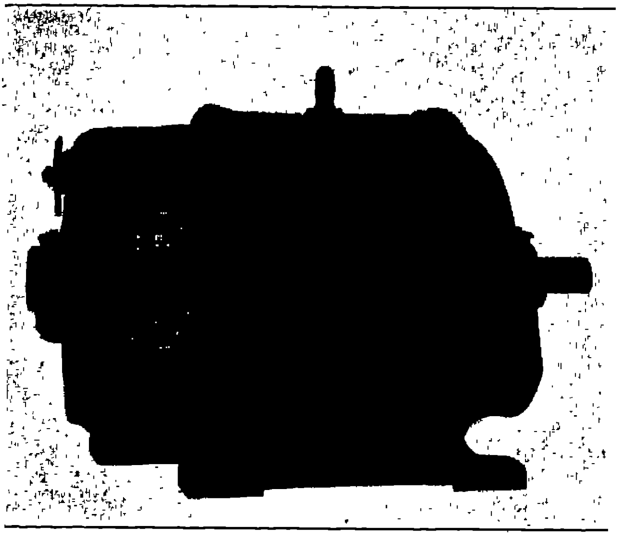


FIG. 57.—Three-phase 17·5 kw., 1750 r.p.m., type P88, Brown, Boveri & Co., Ltd., motor.

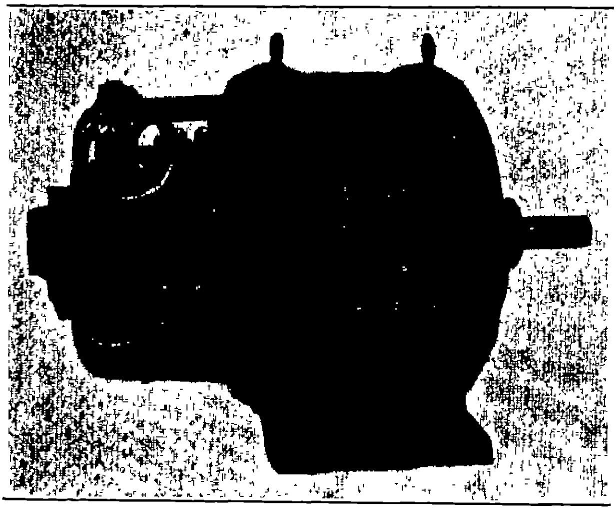


FIG. 58.—37 h.p. motor for use on 200-volt supply and giving specific speeds of 3000, 600, and 330 r.p.m. (Jeumont).

[*To face page* 85.

If the rotor rotates in the opposite direction to the stator field at a speed N, the speed of the stator field with regard to the rotor will be $N + N_s$. The speed of the rotor field with regard to the rotor will be $N + N_s$ in the direction of the stator field, and therefore the speed of the rotor field with regard to the stator will be $(N_s + N) - N = N_s$ again.

It may be stated therefore with a fair degree of accuracy that in a series commutator motor the part of the commutator is that of a frequency converter by means of which the stator and rotor windings may be connected together, thus altering the characteristics of the motor.

The torque exists in an ordinary induction motor only so long as the rotor field is rotating with regard to the stator at the same speed as the stator field is rotating with regard to the stator.

The connection of the stator and rotor windings, the effect of which is to prevent the current induced in the rotor from falling to zero, modifies these conditions entirely.

Starting and Speed Regulation.—Starting, speed regulation, and reversing are carried out by simply displacing the movable brushes. In the present standard types, all the brushes are movable, and can be operated either by hand or by an auxiliary brush-shifting motor.

The brushes must be in the zero position before the switch connecting the motor to the mains is closed. The motor then takes a very small current, amounting to about 10-20 per cent. of the normal current, and corresponding to only about 3-8 per cent. of the full-load input. The starting torque with this brush position is practically zero. By displacing the brushes out of the zero position, the torque and the current rise gradually and absolutely smoothly, and the motor starts up. The direction of rotation of the rotor is always the opposite of that in which the brushes are moved out of the zero position.

When the brushes are brought back towards this position the speed falls: increasing the displacement raises the speed. In this manner it is possible to adjust the speed of the motor to any desired value within the whole speed range, and this for any value of the output.

The series characteristic of the three-phase commutator

motor is of special advantage for starting up, as it develops a high starting torque with a relatively small current, just as a direct current series motor does.

Having a true series characteristic, its speed is unlimited at no-load, and the consequences may be serious in certain cases well known where direct-current machines are employed.

This trouble, however, can be eliminated, and the speed limited by the use of an inductive winding or coil shunting the brushes. The motor, when approaching the limit speed N_1 will behave like an ordinary induction motor with a pseudo-synchronism N_1. It is not usually necessary to provide a special coil: by adjusting the air gap on the stator rotor transformer, the transformer itself will act as a speed-limiting device (Latour patent).

When the motor runs at a speed above N_1, the placing of a coil across the brushes will cause it to slow down, with recuperative effect.

By shifting the position of the brushes the relative position of the stator and rotor poles is modified. Let us consider the case of a bipolar motor; there are two positions where the magnetic couple will be zero. One, when N stator is opposite N rotor, and one when N stator is opposite S rotor.

Two distinct positions correspond to this for the brushes, 180° apart. The case when two poles of same denomination are opposite one another is known as the principal neutral line. If the brushes are set in this position, the motor will not start up, but a very high current will flow, since the fluxes are in opposition and the motor practically short-circuited.

If the brushes are moved slightly one way or the other, the motor will start up and a strong starting torque will result.

The high starting torque results from the repulsion effect of the poles of same denomination on each other.

If the brushes are set on the other neutral line, however, the current flowing through the motor will be small, and the torque considerably lower. In the case of multipolar machines, there will be $2/p$ neutral lines, and p principal neutral lines. It will be seen from this that it is never necessary to shift the brushes to any considerable extent, 20 to 60 electrical degrees being the usual amount for standard machines.

Centrifugal Switch.—If the load of the motor is removed while the brushes have a large displacement, the speed can attain a dangerous value if the brushes are not brought back in time. Where there is danger of such a rise of speed occurring, it is advisable to provide the motor with a centrifugal switch, the operation of which breaks the circuit of the tripping coil of the main switch.

The current in the stator and that in the rotor give rise to a rotating field which should rotate in the same direction as the rotor if commutation is to be satisfactory. Motors which are intended for reversing drives are, therefore, provided with a change-over switch which enables the direction of rotation of the field to be altered by interchanging two of the stator leads, as in the case of a three-phase induction motor. The direction of rotation of the rotor itself does not depend on the position in which the change-over switch may be put, but only on the direction in which the brushes are displaced. In order to prevent the field and rotor from having opposite directions of rotation, the brush gear is interlocked, either mechanically or electrically, with the change-over switch, so that the brushes can only be moved in the way corresponding to the setting of the latter.

Characteristics.—A series of curves dealing with torque, power factor, and efficiency are given and demonstrate better than any lengthy explanation the properties of the machine considered.

It will be seen from these curves that round about synchronism the power factor passes from lagging to leading, that is to say, for speeds above synchronism, when the motor is running with a very light load, the motor feeds back magnetising energy to the mains.

This differs fundamentally from the performance of the induction motor, which is very bad on light loads. It will be seen also that the starting torque increases very rapidly as the brush angle decreases. The efficiency and power factor vary with the output and the speed; nevertheless, the efficiency remains very high over a wide range. The most important advantage of a commutator motor, compared with all other alternating current motors, lies in the fact that it is possible to

vary the speed within wide limits without the efficiency falling off to any great extent. Fig. 59 shows the power factor as a function of the speed of the motor for different brush positions. The corresponding values of the torque and output for the same brush positions are plotted in Figs. 60 and 61. Curves of efficiency and power factor as functions of the speed for two distinct relations between speed and output are given in Figs. 62 and 63. In the first of these, it is assumed that the desired output, which is given by the curve kW, is proportional to the speed, that is, the torque remains constant. In Fig. 63 the output, which is again indicated by the curve kW, is supposed to fall more rapidly than the speed; in other words, the torque of the motor falls off as the speed is reduced.

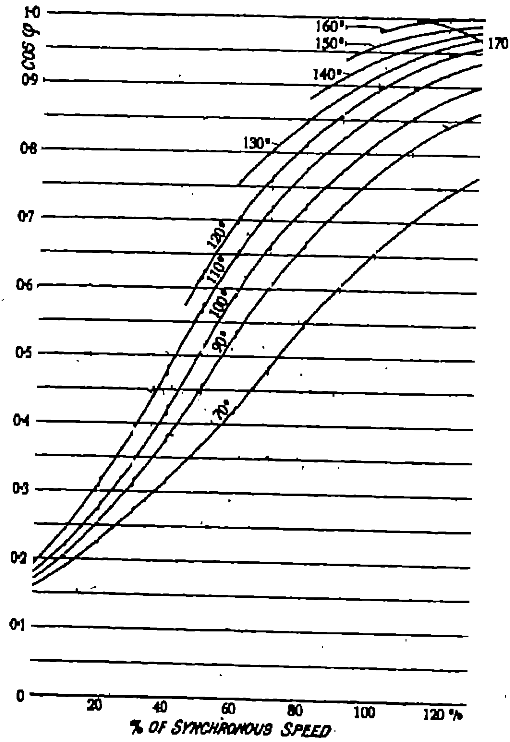


FIG. 59.—Power-factor speed curves for different brush positions.

The curves given in Fig. 64 give a very good idea of the quality of commutation, which, of course, is an all-important point.

The curves show the variation of the commutator voltage as a function of the speed. The voltage is expressed as a percentage of the limit voltage allowable for good commutation. It will be immediately apparent that there is a limit to the amount by which the starting torque can be raised, since com-

mutation difficulties increase at slow speeds, and as the brush angle decreases.

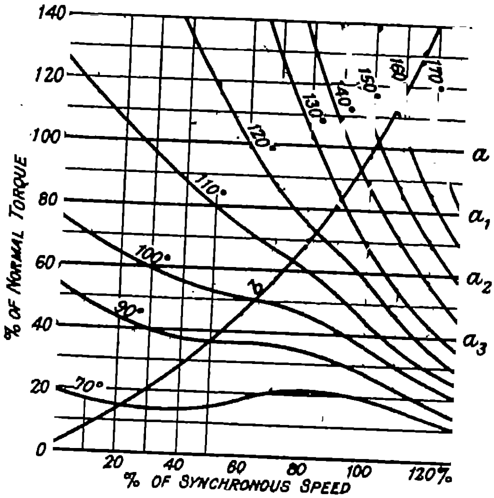


FIG. 60.—Torque-speed curves for different brush positions.

Limits of Speed Variation.—The curves show the limits within which speed variation may be obtained with a constant supply voltage, by shifting the brushes.

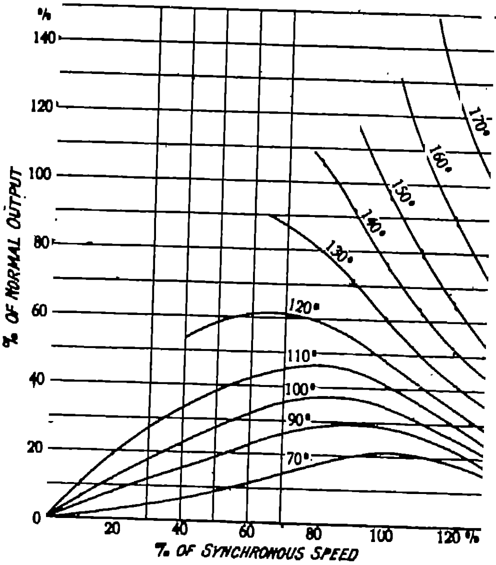


FIG. 61.—Output-speed curves for different brush positions.

In the neighbourhood of synchronism the value of the power factor will be between 0·95 and 1. Above synchronism, we are limited, on the one hand, by the rapid falling off of the torque, and, on the other hand, by the rise of the voltage between commutator segments and consequent bad commutation. Below synchronism the limiting consideration will be the power factor, and also, of course, the voltage between commutator segments, while for very low speeds the question of instability has to be taken into account.

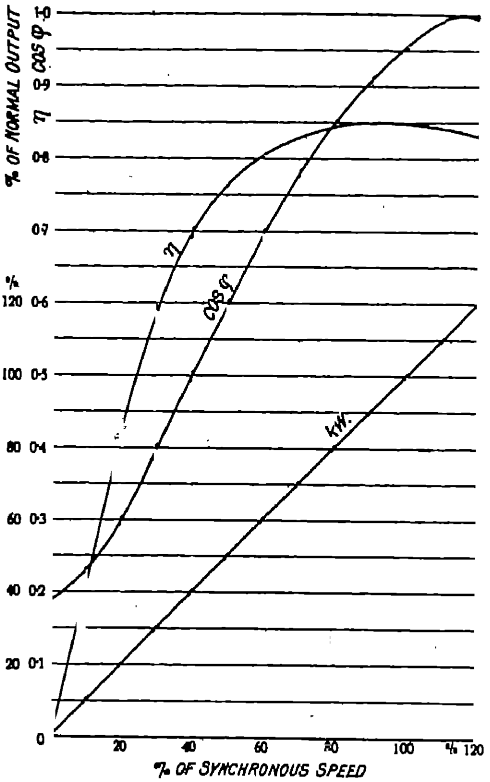


FIG. 62.—Output in kW efficiency η, and power factor $\cos \phi$ as functions of the speed when the latter is varied with constant torque.

The limits of speed variation may be extended in various ways, according to which of the various factors mentioned is the limiting one. If the trouble is due to commutation, the motor may be fed with a variable voltage by means of tappings on the transformer, or by passing, as we shall see presently, from star to delta connections.

The voltage being thus lowered, the commutation will be considerably improved, and no sparking will occur on starting. A great number of commutator motors are fitted with a device of this kind for starting, or when very low speeds are required.

The power factor, on the other hand, is more difficult to deal with, and must always remain a limiting factor to speed

variation. If the trouble lies with the unstable nature of the characteristic at low speeds, the ratio of the transformer between rotor and stator may be altered.

Delta-star Connection.—The power factor of the motor rises to unity (Fig. 59) for high values of the output and speed, whereas it is very poor when both these are low, that is, when the motor is working with the brushes very slightly displaced. It is possible, however, to obtain a favourable power factor even at low outputs by means of the delta-star connection. With this arrangement the motor is connected in delta when the output is large, and in star when it is small.

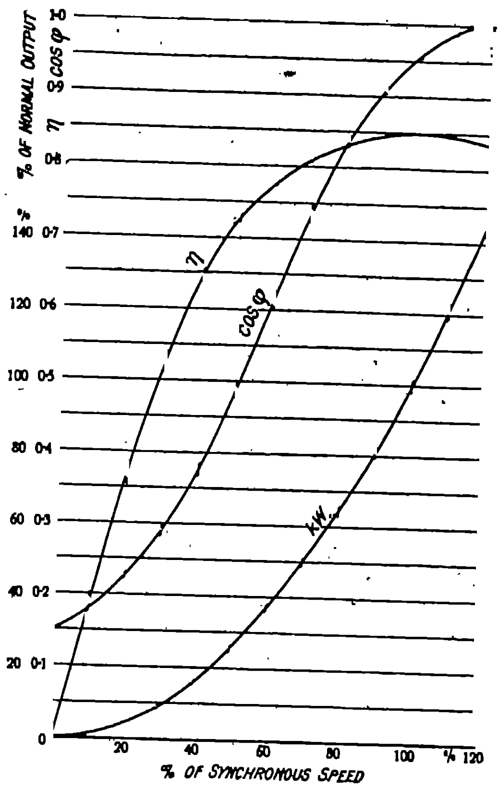


FIG. 63.—Output in kW efficiency η and power factor cos ϕ as functions of the speed when the latter is reduced with rapidly decreasing torque.

Changing over from one arrangement to the other can be done while the motor is running. The brushes must, however, first be brought back to the neighbourhood of the zero position, and only advanced after the delta-star switch has been operated. For any brush position the output of the motor is smaller when connected in star than in delta. A given power is only possible, therefore, with a much greater brush displacement, and consequently the power factor is more favourable (see Fig. 59).

It can be seen from the curves in Fig. 65 that the improve-

ment in the power factor due to the use of delta-star connection is very considerable. These curves refer to the same motor (Brown-Boveri) and motor output which is indicated by the curve kW, and to the same speeds as the curves in Fig. 63.

The curves *a* in Fig. 65, which are identical to those of Fig. 63

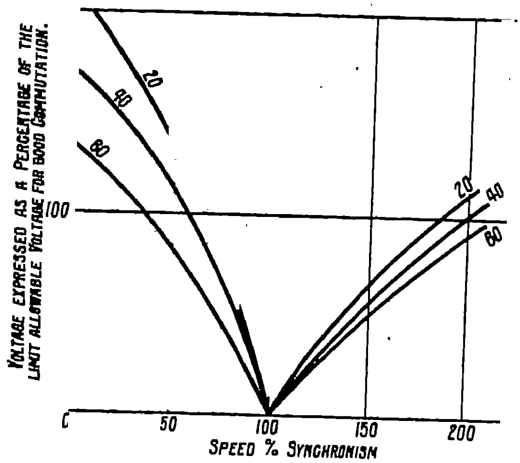


FIG. 64.—Commutation curves.

show the efficiency and power factor of the motor when connected in delta, whereas curves *b* give the values of the corresponding particulars with the motor star connected and working within the range then allowable. If the torque of the motor is to remain constant at all speeds, it is not, as a rule, admissible to change over from delta to star connection.

Stability.—The curves also show that the motor may be unstable for very low speeds, as will be seen from the fact that the torque curve rises at first as the speed increases. When the brushes are displaced by a small amount, the torque remains fairly constant, even with greatly varying speeds. For this reason it is impossible to obtain a definite speed when the brushes are only very slightly out of the zero position, that is to say, at very low speeds and powers; the motor is consequently unstable.

This unstability will, of course, depend on the variation of the load with the speed. In most cases, this torque is either constant, proportional to the speed, or proportional to the

square of the speed (pumps and fans). In cases where the load torque increases with the speed, the motor will always be stable, but, in cases when the load torque is constant, then, should the speed accidentally drop, the motor torque will also drop, and the motor will shut down.

Stable conditions are obtained when the motor continues running at the speed for which it has been adjusted, as long as no change is made in its working conditions or in those of the plant driven by it.

Within the range where unstable operation can occur, the speed with given running conditions may vary between certain definite limits, or, with a practically negligible modification of the conditions of operation, a large variation in the speed may take place. In neither case is satisfactory running obtainable.

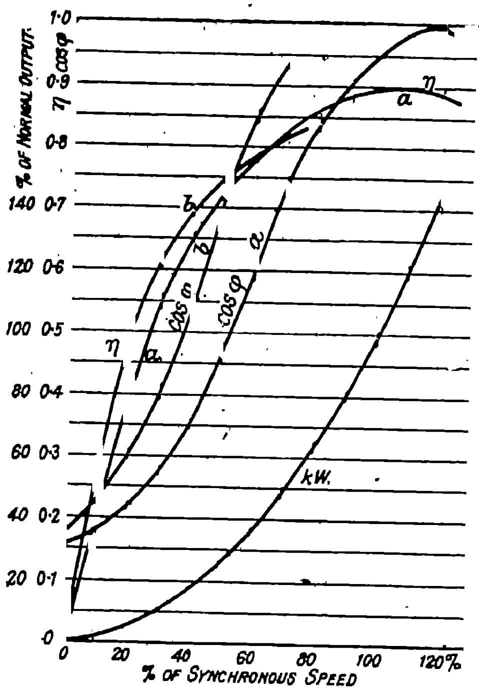


FIG. 65.—Output in kW efficiency η, and power factor $\cos\phi$ as functions of the speed with rapidly decreasing torque.

(*a*) with delta connection.

(*b*) with star connection.

Suppose the load torque to be indicated by the straight line *a* in Fig. 66. With a brush displacement of 90 electrical degrees, the driving torque of the motor is given by the 90° curves in Fig. 60. The motor can then only operate with the speed corresponding to point A. If it were to run quicker, it would develop the torque corresponding to about A_1, which, however, is considerably lower than the load torque at this speed.

The motor would therefore slow down to the speed

corresponding to point A. On the other hand, if the motor were to run more slowly, the reverse would be the case.

Supposing now that the load torque is that given by curve *b*, then the load torque and the driving torque of the motor are almost similar at all speeds between points B_I and B_{II}. The motor will, of course, settle down to a definite speed, but it will always take a considerable time before this state is reached, and if the curve of the load torque is displaced very slightly—due to a change in the friction, for instance—the consequence will be a very considerable alteration in speed. Should the

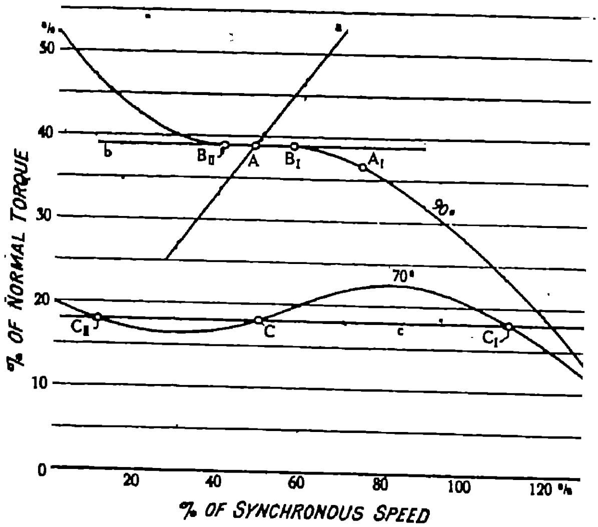


FIG. 66.—Various torque-speed curves.

torque curve of the motor be more like that given by the 70° curve of Fig. 66, the danger of unstable operation will be still greater.

The case of the load torque being that of a straight line *c* will now be considered.

The motor cannot work regularly with a speed corresponding to point *c*. If the speed were to rise even by only a small amount, the driving torque of the motor would be much greater than the load torque. The speed would then increase further to point C_I. Supposing, again, that with the machine running at the speed corresponding to C, a small drop in speed were to

take place, then the machine would immediately slow down to point C_{II}.

No general rule can be stated regarding the kinds of drive where there is a danger of instability, but it may be mentioned that it only happens in occasional cases. The following examples may be given with the view of enabling a clear opinion to be formed on this question.

(1) The torque required by the driven machine is constant quite independently of the speed, as shown by the straight line a in Fig. 60. This is the case with reciprocating pumps, for instance, which work against constant head. The line a cuts the torque curve of the motor in such a way that even when the speed is considerably reduced, the operation of the motor is stable.

(2) The load torque falls rapidly as the speed is lowered. This is shown, for instance, by curve b (Fig. 60), and is the case with fans and centrifugal pumps. Here also the conditions necessary for stable running, even at very low speeds, are fulfilled.

(3) Depending on the adjustment of the driven machine, various values of torque are required with a definite, constant speed. The relation between speed and load torque is then not given by one single curve, but by a group of curves. Such conditions are met with in the case of reciprocating pumps working against a variable head, fans operating with different degrees of throttling, and machine tools taking varying cuts. Let the load torque be shown by four straight lines a, a_1, a_2, a_3. From Fig. 60 it can be seen that, over a considerable range, curve a_3 corresponds closely to the driving torque of the motor with brushes at 90°, hence the operation of the motor would not be stable at low speed and reduced output.

By changing over to star connection as mentioned above, the motor can develop a given torque only with a much greater brush displacement than when connected in delta. Since the danger of instability is only present when the displacement of the brushes is small, it is evident that delta-star connection permits stable running to be obtained. In occasional cases, with difficult operating conditions which cannot be met by the adoption of the delta-star method, stable running can be

attained by the temporary use of resistances (Brown-Boveri patent).

It is assumed in the torque curves of Fig. 60 that the motor is provided with a series transformer. Should this not be the case, the torque curves bend sharply down at low speeds even with a medium displacement of the brushes. The shape of the curves is then more nearly that shown in Fig. 67. The danger of unstable running is consequently greater with the stator and rotor connected directly in series than when a transformer is inserted between them.

It may be mentioned here that some engineers are of the

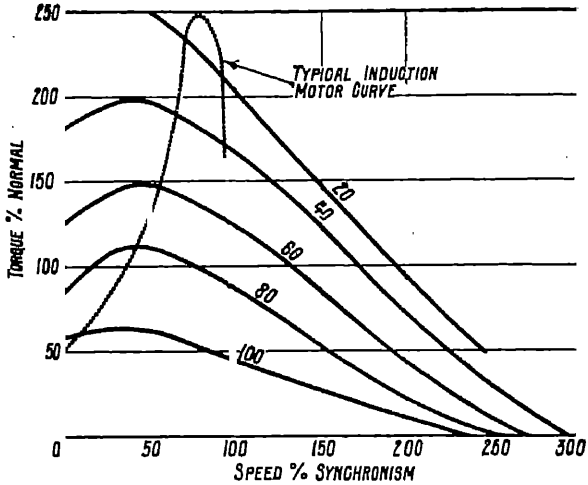


FIG. 67.—Typical speed-torque curves in absence of transformer.

opinion that the best means of preventing unstable operation is to make the motor with both movable and fixed brushes. With such an arrangement there is certainly no possibility of having curves like those in Fig. 67. On the other hand, a rapid increase of torque with falling speed, as was shown to be necessary in example (3) for obtaining stable conditions, cannot then be obtained when the brush displacement is small.

Further, the power factor falls off very much at low output, and the utilisation of the motor as a whole is less favourable than with the three-phase motor as usually made, that is, with all the brushes movable.

Regenerative Braking and Prevention of Reversal.—If the

brushes are brought back through the zero position and displaced in the opposite direction while the motor is running, it will operate as a generator and return electrical energy to the supply mains. It then absorbs mechanical energy and acts as a brake, the magnitude of the braking action depending on the extent to which the brushes are displaced. In general, resistances must be switched into the circuit so as to prevent the undesirable occurrence of self-excitation during braking. This resistance, however, only absorbs a fraction of the power returned by the motor.

If the motor is not specially intended for regenerative braking, its speed must not be reduced by reversing the position of the brushes. Motors which are intended for running always in the same direction are provided with a stop, so that the brushes can only be displaced on one side of the zero position. Motors used for a reversible drive must, of course, be so constructed that the brushes can be moved in either direction. With such motors an interlocking device can be fitted to prevent any possibility of the brushes being put over in the reverse direction while the motor is running.

The Compound Commutator Motor.—It is necessary, for certain applications, to design a motor having an extended scale of speeds, and a very slight variation of speed between no load and full load. Moreover, the scale of speeds must extend above and below synchronism. The principle is based on the following considerations.

In a series motor the commutator voltage is approximately proportional to the slip. If, therefore, we apply a variable voltage to the commutator, in phase with the rotor voltage, the motor will run at a speed such that the voltage induced by the resultant flux balances the applied voltage. By altering the latter, the speed may be varied.

The simplicity of this solution is very remarkable, but the true problem lies in devising an effective method of obtaining a *variable voltage* that will be constantly *in phase with the rotor voltage.*

In a series motor the stator and rotor voltages can be represented as two vectors at an angle equal to the angle between the brushes and the neutral line. Let us now go back to the

theory of the rotating field double induction regulator. This apparatus consists of two induction motors, of which the stators are connected in parallel, and the rotors in series, the fields of the two motors rotating in opposite directions.

The rotors are coupled to a common shaft, which may be shifted through any given angle. If the stators are fed from a supply voltage E, the resultant induced voltage in the rotors will be at an *angle* with E which depends entirely on the *relative position* of the two rotors, while the *value* of the resultant voltage will vary from zero to a maximum when both rotors are *simultaneously* shifted through an angle of 180° (electrical).

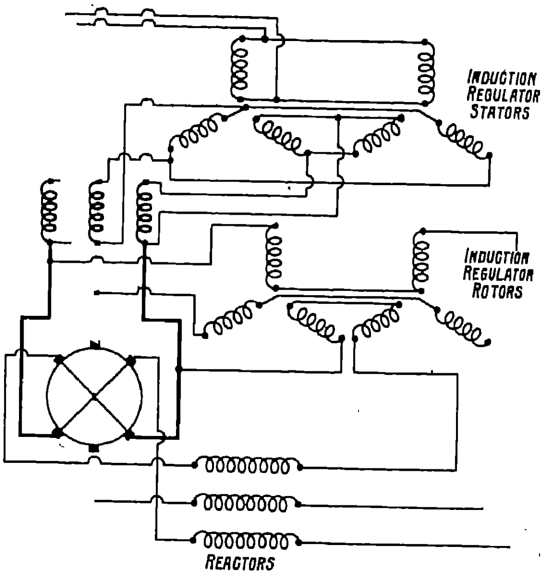


FIG. 68.—Compound commutator motor (Jeumont).

Bearing this in mind, if we connect the stators of the regulator in parallel with the stator of the commutator motor, and the rotors of the regulator, which are connected in series, to two diametrically-opposed brushes, the two rotors of the regulator being set at a relative angle equal to that of the commutator brushes, by shifting the position of the two rotors *together*, any required speed can be obtained on the commutator motor, above or below synchronism.

This particularly neat solution to a difficult problem is

shown (Fig. 68), and is due to the Ateliers de Jeumont. Such motors are made up to such high ratings as 600 and 800 h.p., and are absolutely satisfactory both as regards speed regulation and efficient commutation. Three reactors are shown in the diagram; the object of these is to regulate the amount of slip between no load and full load, and also limit the commutation voltage on starting. We will return to the Compound Commutator motor later.

Field of Application of the Three-phase Commutator Motor.—As a rule, three-phase commutator motors are only employed for drives requiring much speed regulation or very frequent starting, as only in such cases are their advantages fully utilised. It is here assumed that a series characteristic is desired, or, at least, not found inconvenient. A series motor works quite as favourably as a shunt motor with drives, such as pumps and fans, which always take the same power at a given speed. The same is the case when the brushes are continually adjusted, either by hand or automatically, in order to obtain the exact speed required corresponding to the load on the motor at the moment—conditions that are frequently found with rolling mill drives. It is often necessary to arrange for reduction of the motor speed as the load rises, so that the motor and the mains are freed from heavy peak-loads, or continued overloads; under such conditions a motor with a series characteristic is much more advantageous than a shunt machine. However, with drives requiring a constant motor speed even with a greatly varying load, as with paper-making machinery, for instance, a series motor must not be employed.

The three-phase commutator motor has to compete, in general, with the single-phase commutator motor, and the three-phase induction motor. In common with the single-phase machine it has the important advantage of high starting torque and of speed regulation without the necessity of dissipating energy in resistances. It is also a better machine in that its efficiency and power factor are more favourable, as well as by the fact that each phase of the three-phase system is equally loaded; this point is of special importance in installations requiring only a single motor.

Further, large three-phase commutator motors, even

including the series transformer, are cheaper than single-phase machines of the same output. The advantage of the latter type lies in its simpler arrangement of connections. While this may be worth considering with machines of low output, it is of very slight importance with larger machines. Moreover, as the series transformer constitutes a large proportion of the total cost of small three-phase machines, single-phase phase units of the same power are somewhat cheaper.

When comparing the commutator motor with the three-phase induction motor, it is found that the advantages of the former are all the more prominent, the more frequently either starting against load or considerable speed regulation is required. With the induction motor the resistance inserted in the rotor circuit is greater, the larger the reduction of speed required, and the higher the torque to be developed by the motor, the greater the amount of energy absorbed by the resistance. Since there are no such losses with the commutator motor, a saving of energy is possible which increases with the extent of speed regulation and the magnitude of the torque required at reduced speed. It is frequently found that the saving thus effected suffices to pay off in a short time the higher first cost of the commutator motor. Further, it may be set down as an advantage of the commutator motor that no resistances need be provided, and also that the heating arising from the use of the latter apparatus does not enter into consideration.

The speed at which the induction motor operates most advantageously is the highest speed attainable with such a machine. With the commutator motor, on the contrary, it is possible with light loads to run at a speed much above the most favourable full-load speed. This often allows the plant driven by it to be utilised in a fuller measure than would otherwise be possible. Moreover, while with the induction motor only certain definite steps of speed and torque can be obtained; any desired value is possible with commutator motors. The change from one value to another takes place absolutely smoothly, which is of great advantage, especially at starting, as the current taken from the mains rises very gradually, corresponding to the rate of displacement of the brushes, and so no sudden peaks have to be reckoned with.

The torque developed by the induction motor is roughly proportional to the current, whereas a high-starting torque is developed by the commutator motor with a relatively small current.

Three-phase commutator motors have been used with great success for driving such machines as fans, blowers, pumps, winding engines, rotary printing presses, locomotive-traversers, briquette presses, and many kinds of machine tools.

The photographs reproduced in this chapter show some typical examples of commutator motors. Fig. 58 shows a small 37 h.p. motor for use on a 200-volt supply, and giving a range of speeds between 3000 and 300 r.p.m. Fig. 56 shows a larger motor designed for driving mine fans, and wound for 3100 volts. It develops 450 h.p., and its speed varies from 480 to 230 r.p.m.

Fig. 47 shows a vertical motor rated at 460 h.p. for driving pumping machinery, and wound for direct connection to a 6600-volt supply. These three motors are built by the Forges et Ateliers de Constructions Electriques de Jeumont (Nord).

Figs. 55 and 57 show motors by Brown, Boveri & Co., Ltd., the first a small three-phase machine, and the second a three-phase 17·5 kw., 1750 r.p.m., type P88 motor.

Amongst three-phase commutator motors manufactured in this country for medium powers, those developed by the British Thomson-Houston Co. are interesting, as they are somewhat different from the usual types.

The motors known as Type CH are provided with the following windings, the primary and secondary being arranged inversely to those of the ordinary induction motor :—

(1) Primary winding located on the rotor, and by means of slip-rings on the rotor, connected to the supply leads.

(2) Secondary winding located on the stator.

(3) Regulating winding placed in the same slots on the rotor as the primary winding.

The regulating winding is connected to the commutator and thence, by means of the brushes, in series with the secondary winding on the stator.

Within its normal speed range, the motor has practically the same characteristics as a direct-current shunt-wound motor with speed variation by field control, with the exception that

the speed of the former does not vary with the temperature to the same extent as does that of the latter. Normal speed variation is obtained simply by turning the hand wheel provided, which, through rack and pinion gear, changes the position of the brushes on the commutator. The movement of the brushes can also be effected very conveniently from a distance either mechanically or electrically by means of a small pilot motor coupled to the brush-shifting spindle, and controlled by push-buttons. The latter system has the advantage that when the main motor is switched off, the pilot motor automatically returns the brush gear to the correct position for re-starting. This type of motor, unlike the D.C. variable speed, shunt-wound motor, where the maximum torque is developed at the lowest speed and decreases as the speed increases—exerts a constant torque throughout the whole speed range, i.e. the output is directly proportional to the speed.

The normal speed range of the standard motor is 3 : 1, but special speed ranges can be designed to suit any requirement within reason. An interesting point is that the motor operates at speeds above or below the synchronous speed, and at any speed between the maximum and minimum values. When running at synchronous speed, the motor operates exactly as an ordinary induction motor. Under this condition no part of the regulating winding is in circuit, the secondary winding being short-circuited through the brushes across one or more commutator segments.

According to the amount that the two sets of brushes, with which the motor is provided, are displaced in one direction or the other, so the speed will vary either above or below synchronous speed. It is usual, therefore, to select a synchronous speed about midway between the maximum and the minimum speeds desired.

The difference between the no-load speed and the full-load speed for any brush setting is approximately 5 per cent. to 10 per cent. of the maximum speed of the motor, the exact percentage depending on the size of the motor. In some cases a creeping speed is required, and this can be obtained by inserting a small resistance in each phase of the stator winding.

This type of motor is more stable than the ordinary induction

motor when running at creeping speeds, and hence lower creeping speeds can be obtained. The stability of an asynchronous motor, i.e. liability to drop out of step with fluctuations of load, when running at creeping speeds, depends on the ratio of the creeping speed to the normal operating speed—the smaller this ratio the greater the stability.

The commutator motor has normal operating speeds much below the synchronous speed, hence this ratio is smaller than would obtain in the case of a slip-ring induction motor, where the normal operating speed is only slightly less than the synchronous speed.

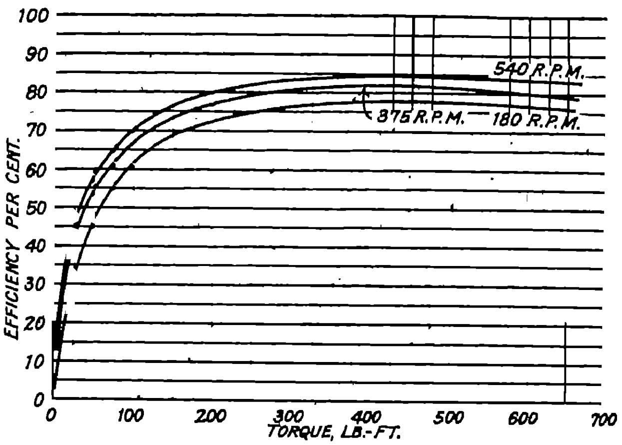


FIG. 69.—Characteristic curves obtained with a 50/17 h.p., 540/180 r.p.m., 400 volt, 25-cycle motor (Siemens-Schuckert).

A plain circuit breaker only is required to start the standard motor. A switch is provided on the brush gear so that an electrical interlock can be arranged with a suitable main circuit breaker in such a manner that the latter cannot be closed unless the brushes of the motor are set in the minimum speed position, i.e. the correct position for starting. Under these conditions the motor will exert a starting torque of not less than one and a half times full-load torque with a line current of approximately one and a quarter full-load current.

As regards commutation, for a motor of given horse-power, the power dealt with by the commutator is only a fraction of the total, as, therefore, the commutator voltages and currents

are small, liberal design limits can be used, and hence any sparking which may occur is negligible. Characteristic curves obtained on test from a 50/17 h.p., 540/180 r.p.m., 400 volts, 25-cycle, three-phase motor are shown in Figs. 69 and 70, and

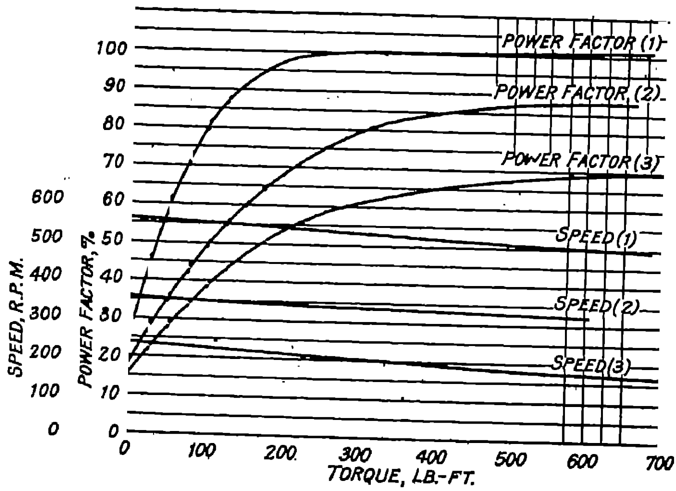


FIG. 70.—Characteristic curves obtained with a 50/17 h.p., 540/180 r.p.m., 400 volt, 25-cycle motor (Siemens-Schuckert).

are typical of all these motors. The curves are plotted for conditions at maximum, mean, and minimum speeds.

Construction.—The rotor core consists of laminations of sheet iron of high permeability, slotted on the periphery to receive the windings, and clamped under pressure between end flanges. It is provided with radial ventilating ducts to allow free circulation of air through the body of the rotor. At the ends of the rotor, and also in each ventilating duct, steel "I" beam spacers are provided to support each tooth.

The primary winding is located beneath the regulating winding, and has former-wound coils of a definite pitch, the ends being brought out to suitable slip-rings mounted on the shaft. The regulating winding consists of former-wound coils of a definite pitch, and the ends of each coil are connected to the commutator.

Commutator.—This is built up of hard-drawn copper segments of ample wearing depth, insulated by means of selected reconstructed mica, and from the clamping rings and shell by means of cones and a sleeve composed of similar material

The shell is forced into position and rigidly keyed to prevent any relative movement between the rotor windings and the commutator. The shell is provided with ventilating ducts.

The brushes are of graphitic carbon, and are carried in brush-holders of the clock-spring type, so constructed that the pressure on any brush is uniform throughout the life of the brush and can be readily adjusted.

Shunt Motors.

There are several different arrangements of windings for three-phase shunt motors, but the essential features are a phase-wound stator, an armature winding and commutator substantially identical with those of a direct-current machine, and some means of obtaining a variable voltage (at supply frequency), this voltage determining the speed at which the motor runs. The speeds thus obtained commonly range from one-half to one and a half times the synchronous speed.

The adoption of the more special forms of alternating current motors for industrial purposes has undoubtedly been retarded by the fact that comparatively few engineers are really familiar with the operating characteristics of these machines. This has been particularly the case where alternating current commutator motors are concerned, and in proceeding to discuss the properties of the three-phase shunt motors, it is proposed to take as example the type manufactured by the Siemens-Schuckert-werke under the main German patent No. 260,319. The exceptionally instructive characteristic curves relating to this motor are reproduced from a brochure issued by the makers.

Energy from the alternating current mains is supplied to the rotor through slip-rings connected to a three-phase winding which is generally placed at the bottom of the rotor slots. The three-phase secondary windings, on the stator, are not connected to each other, as in an ordinary three-phase motor, but are connected each to a pair of adjustable brushes on a commutator, the latter being connected to an auxiliary winding on the rotor. The auxiliary winding is an ordinary direct-current drum winding, and though this may be connected electrically to the slip-ring winding, it is preferable to keep the two windings electrically distinct; the maximum voltage on the commutator is then from 60 to 80 volts, whereas with the other

arrangement the commutator is electrically connected to the alternating current supply, and must not be touched while the motor is running. A further advantage in keeping the rotor windings electrically distinct is that the three-phase slip-ring winding can be connected either in delta or star, thus giving a voltage change in the ratio of $1 : \sqrt{3}$, and making possible higher efficiency and power factor where motors have to run for prolonged periods at fractional loads.

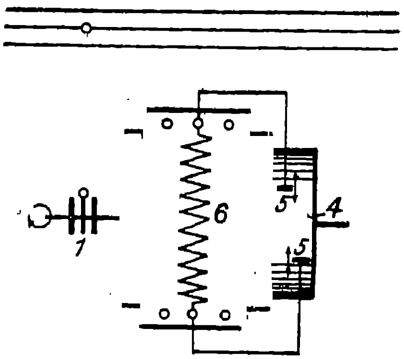


FIG. 71.—Diagrammatic arrangement of motor.

The general arrangement of the motor is shown diagrammatically by Fig. 71, in which the supply lead, stator coil, and brushes for one phase only are shown. The corresponding brushes in each pair are spaced 120 electrical degrees apart, and by varying the distance between the brushes of each pair, an E.M.F. of any desired magnitude and phase (and of the supply frequency) can be applied to the stator phases. Referring to Fig. 72, the E.M.F. applied to each phase of the stator winding is continuously regulable between the limits $\pm e_{max}$.

Speed regulation is thus obtained practically without loss. There is no dissipation of energy in regulating resistances, and no regulating switch gear, variable transformer, or other accessory apparatus is required. Normally, the brush-

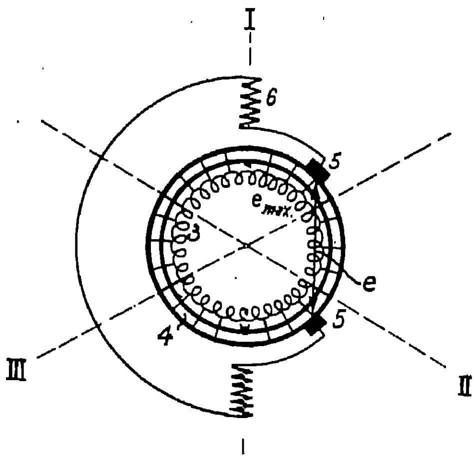


FIG. 72.—Variation of E.M.F. applied to each phase.

setting is changed by a hand-wheel and gear, but an automatically controlled servo-motor may be used for the purpose. The slip-rings may be connected directly to alternating-current supply at pressures up to about 550 volts; for higher pressures a step-down transformer is required.

Method of Working.—When the three slip-rings are connected to a constant three-phase voltage there is established in the motor a rotary field inducing, in the slip-ring and commutator windings, E.M.F.'s which are entirely independent of the rotor speed. As regards the stator, however, the rotary field is practically constant, but its speed, relative to the stator, depends on the speed of the rotor. The "slip voltage" E*s* of the stator winding therefore varies with the machine speed, being zero when the rotor is running synchronously. In order that the motor may run at a certain speed on no-load, the slip-voltage e of the stator at this value of rotor speed must be balanced by a voltage $-e$, equal in magnitude and frequency but opposite in phase. The E.M.F. required for this purpose is taken from the commutator by shifting the brushes as required, and according as the auxiliary voltage is negative or positive, the motor runs below or above synchronism. The limiting speeds are determined by the ratio of the maximum auxiliary voltage, e_{max} to the slip-voltage E of the stator at standstill. For example, if $e_{max}/E = \frac{1}{2}$, the motor can be operated at any speed from one-half to one and a half times synchronous speed by brush displacement alone; the range of speed regulation is then 1 : 3.

The maximum commutator voltage (e_{max}) is determined by considerations of commutation, and the lower the standstill voltage E of the stator for a given commutator voltage, the wider the range of speed regulation. On the other hand, for constant horse-power the commutator current varies inversely with the standstill voltage of the stator, hence a wider speed range involves a longer commutator, more brushes, and increased commutator loss. In the interests of capital economy and operating efficiency, no wider range of speed variation should be specified than is actually required. For most practical purposes, the standard speed range of 1 : 3 is quite sufficient. If a greater variation is required temporarily, it may

best be obtained by means of a variable resistance R in each phase of the stator circuit. Speeds from the lowest attainable by brush displacement down to practically standstill can then be obtained, but it must be understood that there are regulation losses and the shunt characteristic of the motor is lost when any part of the resistance R is in circuit ; under these conditions the motor behaves as an asynchronous machine with slip-regulating resistance.

By the temporary insertion of resistance in the secondary (stator) circuit, any three-phase shunt motor of this type can be started like an ordinary induction motor. The net voltage $(E - e)$ determining the value of the starting resistance is, however, only $\frac{1}{2}E$ (assuming a speed range of 1 : 3 by brush displacement, e being then $\frac{1}{2}E$), hence the starting resistance is only half of that required by an ordinary induction motor. Small machines can be switched straight on to the mains, the brushes being first set in the minimum speed position. Owing to the partial balancing of the stator voltage, the current rush and mechanical shock are considerably less than in a squirrel-cage motor of equal power.

If the auxiliary voltage taken from the commutator be displaced in phase with regard to the stator voltage, by shifting the brush axis with regard to the stator axis, secondary currents are produced which affect the primary power factor. Theoretically, power factor correction can be effected at any speed, but the requisite brush gear is complex. In most cases, it is sufficient to take from the commutator a voltage in phase with the stator voltage since the negative action of leakage (at hyper-synchronous speeds when operating as a motor and at sub-synchronous speeds when working as a generator) effects sufficient phase-compensation. Supplementary phase-correction is advisable at low speeds in the case of motors which have then to carry heavy overloads, because the stalling torque is thus considerably increased.

Operating Characteristics.—The operating characteristics of the three-phase shunt motor described are shown in very instructive form by the curves in Fig. 73, which relate to brake tests at constant torque and variable speed on a 20 kw. machine. The regulating voltage from the commutator was in phase with

the stator voltage, and the secondary current I_2 increased towards each limit of speed owing to the effect of the variable secondary leakage. The primary power factor $\cos\phi_1$ reached

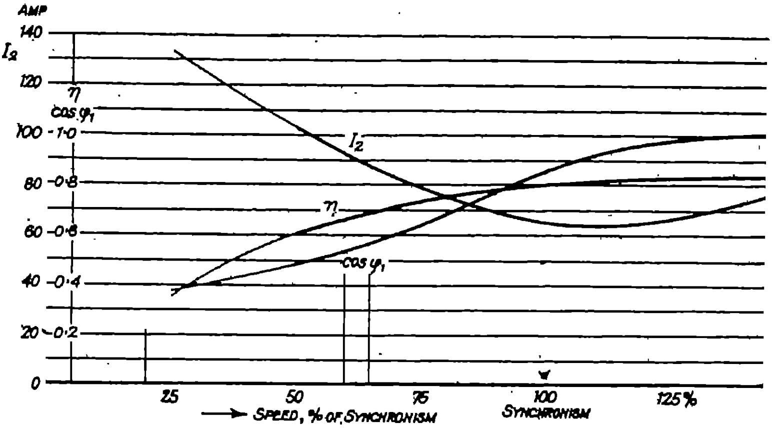


FIG. 73.—Characteristic curves of three-phase shunt motor *at constant torque* (20 kw., 220-380 volts, 50 cycles, 1000 r.p.m.).

high values at hyper-synchronous speeds owing to the effect of the negative leakage already mentioned. The efficiency remained nearly constant over a wide range of speed, but de-

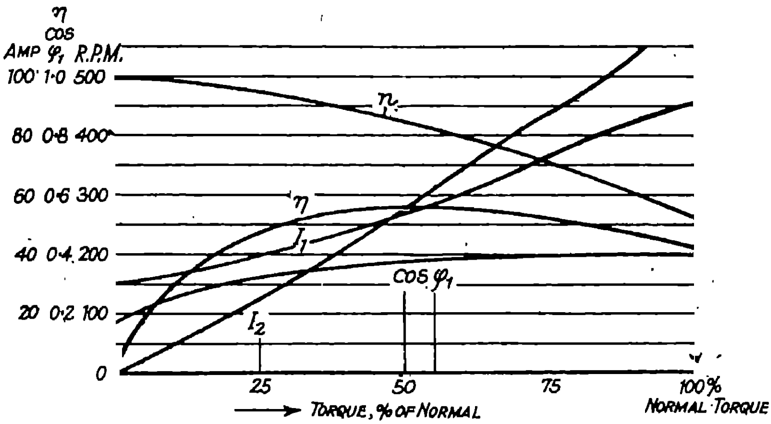


FIG. 74.—Brake curves of three-phase shunt motor; *torque variable* (20 kw., 220-380 volts, 50 cycles, 500 r.p.m.).

creased considerably at the lower speeds in consequence of the heavier wattless current. Further interesting information is to be derived from Figs. 74 to 76, showing the characteristics

of the same motor plotted against values of torque from zero to normal, with brush settings corresponding to minimum, mean, and maximum speeds (500, 1000, and 1500 r.p.m.) respectively.

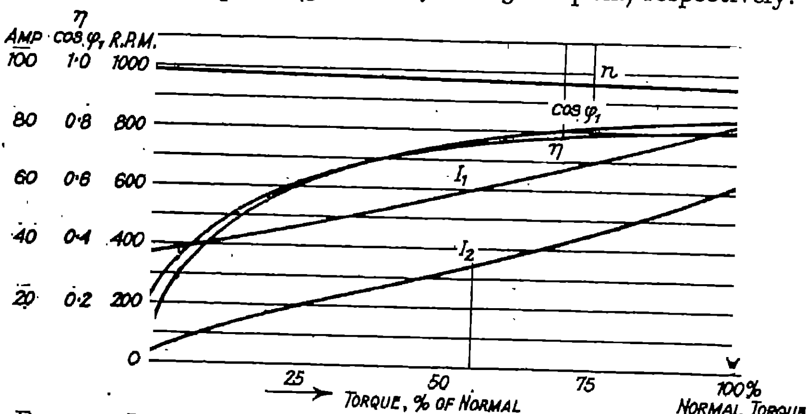


FIG. 75.—Brake curves of three-phase shunt motor; *torque variable* (20 kw., 220-380 volts, 50 cycles, 1000 r.p.m.).

The curves *n*, of speed against torque, show clearly the shunt characteristics of the machine. The percentage decrease in speed from light load to full load is naturally greater at the

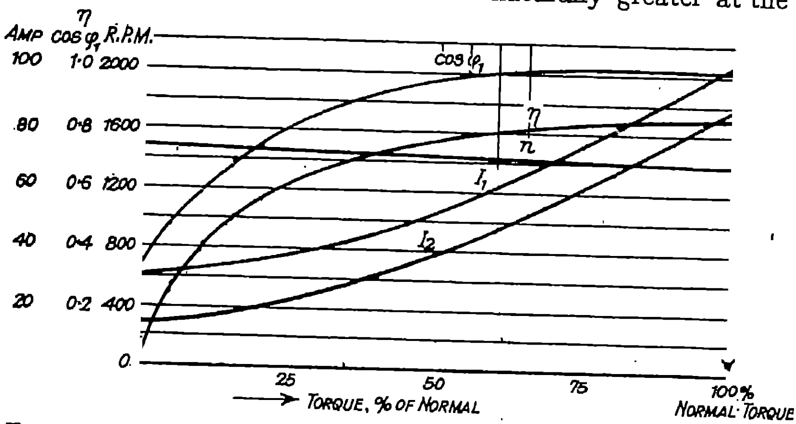


FIG. 76.—Brake curves of three-phase shunt motor; *torque variable* (20 kw., 220-380 volts, 50 cycles, 1500 r.p.m.).

lower speeds; within the normal range of operation it is usually from 4 to 8 per cent. Figs. 77 and 78 show curves of efficiency and power factor respectively for various torques and speeds.

The direction of rotation of the three-phase shunt motor,

like that of the ordinary induction motor, is determined solely by the rotating field so that, to reverse the machine, it is only necessary to interchange two of the slip-ring connections, pro-

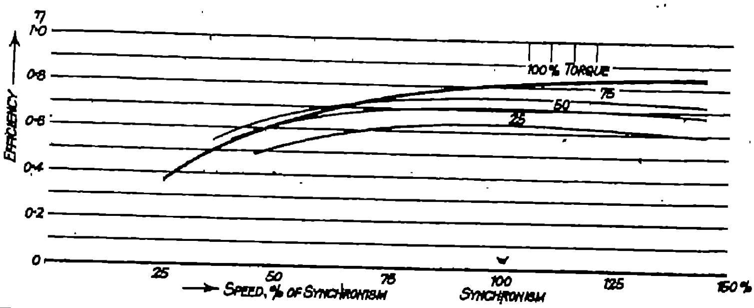


FIG. 77.—Efficiency curves of three-phase shunt motor *at constant torque* (neglecting the water-friction of the brake), (20 kw., 220-380 volts, 50 cycles, 1000 r.p.m.).

vided that the voltage tapped from the commutator is in phase with the stator voltage. If, however, the brush axis be displaced in order to obtain supplementary improvement of power

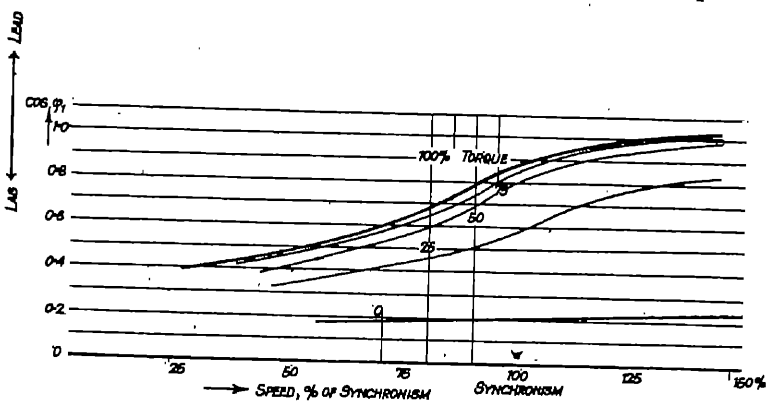


FIG. 78.—Power-factor curves of three-phase shunt motor *at constant torque* (20 kw., 220-380 volts, 50 cycles, 1000 r.p.m.).

factor, maximum compensation is obtained at light load and minimum speed. Under these conditions the secondary current is greatly increased, and the primary power factor becomes leading (see Fig. 79). Special attention must be paid to these characteristics if the machine is to be run for considerable periods on light loads at the lower speeds, and it is advisable,

in such cases, to provide less compensation in the first instance or to moderate its effect by connecting a small supplementary

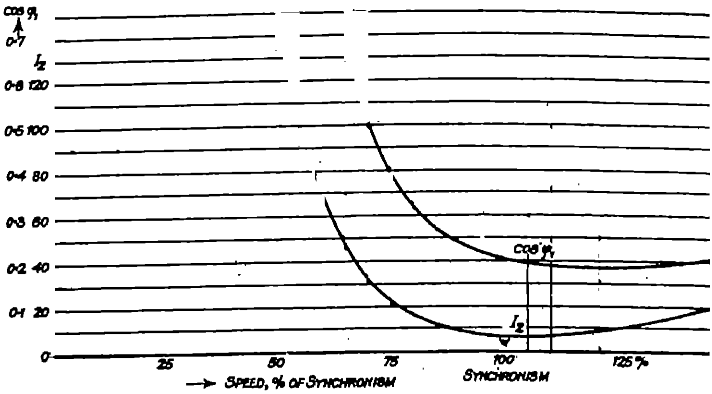


FIG. 79.—Light-load values of secondary current (I_2) and primary power factor ($\cos \phi_1$) for three-phase shunt motor with supplementary compensation (20 kw., 220-380 volts, 50 cycles, 1000 r.p.m.).

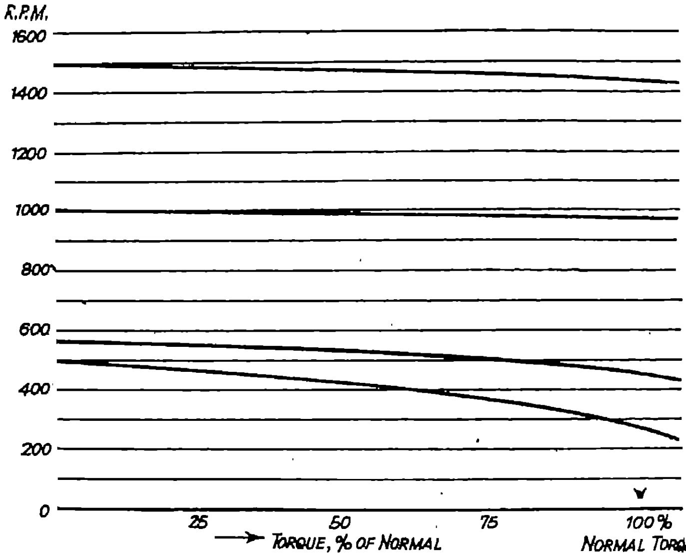


FIG. 80.—Speed curves of three-phase shunt motor; *torque variable* (20 kw., 220-380 volts, 50 cycles, 1000 r.p.m.).

ohmic resistance in the secondary circuit. It is even safer, where such loads are concerned, to dispense with special compensation at the lower speeds. The secondary current is then

roughly proportional to the torque throughout the range of regulation, and compensation at the higher speeds is effected automatically by the leakage flux as already explained. Experience shows that practical requirements are best met by keeping the brush axis coincident with the stator axis; all motors of this type are therefore so adjusted before despatch, but the brush frames can be subsequently displaced, if desired, so as to improve the power factor at the limiting speeds.

A three-phase shunt motor acts as a generator when the rotor is driven by any external force. There are no disturbing self-excitation phenomena, such as occur in three-phase series and single-phase repulsion motors, hence there is no need to use damping resistances which dissipate energy and reduce the efficiency of regenerative braking.

CHAPTER V.

CASCADED INDUCTION-MOTOR COMMUTATOR-MOTOR SETS, AND POWER-FACTOR CORRECTION.

PART I.—GENERAL CONSIDERATIONS.

HAVING obtained a clear idea of the theory of single-phase commutator machines, we have seen that the polyphase type is identical in every respect as regards its analytical treatment.

In the present chapter it is proposed to deal with one of the most important applications of commutator machines—the compensation of the reactive component.

In any plant which comprises a number of machines fed from a common supply, the total power is provided by the alternators at the supply stations at the expense of a certain amount of fuel.

The total wattless energy is equally provided by the alternators, and indirectly corresponds to an extra fuel consumption, since the wattless energy causes an increase in heating and voltage drop in both alternators and mains.

Let us consider the influence of the power factor on the first cost of a power station, and the efficiency of the generators.

Effect on First Cost.—Assuming that each unit at the power station should feed 10,000 kw. to the mains, the turbine rating will immediately depend on this figure, and should be 10,000 kw.

But with the alternators this is not the case. The amount of electrical energy which a machine can generate is limited by heating considerations. For any given frequency and voltage the heating depends on the value of the current flowing through the stator, and through the rotor, and there is no immediate dependence between the two. There will be a limiting value for the stator current, and a limiting value for the rotor current, either of which will independently limit the total generator output. The normal output of the stator is

limited, therefore, by the kilovolt-amperes generated by the alternator.

The output of the stator will consequently fall off when the power factor drops. A stator with an output of 10,000 kw. when $\cos \phi = 1$ will have an output of only 7000 kw. when $\cos \phi = 0{\cdot}7$.

The necessary excitation current, moreover, also depends on the power factor, and will increase to the extent of 30 per cent. to 40 per cent. when the power factor drops from unity to 0·7. It follows that the Joule losses will be practically double when the power factor drops to 0·7, which means either extra ventilation or a larger rotor.

For a 0·7 power factor we will need a much larger alternator than would be the case for unity power factor; the stator will be some 40 per cent. longer, and the rotor considerably larger.

Effect on Efficiency.—The stator Joule losses for a given output will be inversely proportional to the square of $\cos \phi$. They will therefore be twice as great in the new machine as in the original one.

The rotor Joule losses, we have seen, will be more than doubled.

In every way, therefore, a generator is handicapped by a low power factor, both as regards efficiency and first cost.

Suppose, again, that alternators in a power station have been installed for an output of 10,000 kw. with a 0·8 power factor, and that the power factor is actually only 0·7. The turbine can produce 10,000 kw., but the alternator cannot cope with such an output; the stator, at maximum load, can only give 12,500 k.v.a., that is, 8750 kw.; the rotor cannot even cope with the latter figure, and the output will drop to about 8000 kw.

Tariff Considerations.—There is a further and very strong incentive to good power factor operation in the practice of charging for wattless energy, and consumers, when they are not moved by considerations of general economy, will realise the incongruity of paying for a fictive power which they can very well eliminate by the judicious installation of machinery

Methods of Compensation.—Any rotary machine provided with a commutator, or any induction motor used in conjunction with a commutator machine, can be made to feed back wattless

energy to the mains and thus compensate for low power factor.

This application of commutator machines is perhaps the most important one of all. The methods used may be generally divided into two main classes, the second of which alone is of direct interest to us in these pages, although the first is worthy of passing mention for the sake of clearer understanding. The two classes are :—

(1) Synchronous machines with direct-current excitation.

(2) Polyphase induction commutator machines alone, or in conjunction with ordinary induction motors.

(1) **Synchronous Machines with Direct Current Excitation.**—*A*. The best-known type is the ordinary synchronous motor with direct-current exciter. When such a machine is over-excited, it will feed back wattless current to the mains.

When such a machine is used solely for raising the power factor, it is known as a synchronous condenser, although we prefer the name, synchronous compensator. In this case the machine can be designed with a narrow air-gap and a high armature reaction, which could not be done for a motor designed to pull a load.

B. **Synchronised Induction Motors.**—Here again the author must admit his preference for the term synchronised asynchronous motor. All such machines are merely ordinary induction motors provided with a direct-current variable voltage exciter, and the principle was first introduced by Danielson in 1902.

The motor starts up in the usual way as an induction motor, and when it reaches the neighbourhood of synchronous speed, two of the rotor phases, in series, are fed with direct current from the exciter. The motor then synchronises automatically and runs as an ordinary synchronous machine.

The main advantage of the synchronised asynchronous motor is that it possesses a high-starting torque.

The essential difference between this type of motor and the ordinary synchronous motor, however, depends on the fact that the load characteristics are very different. The synchronous motor will pull out should a heavy overload occur, whereas the synchronised induction type will merely pass back to in-

duction motor conditions, and will return to synchronism when the overload dies down.

(2) **Polyphase Induction-Commutator Machines.**—In this case, which will be fully dealt with in this chapter, the magnetising current is provided by a polyphase commutator machine alone, or running in conjunction with an induction motor, or combined with an induction motor.

Use of Commutator Motor Units.—The use of commutator motors alone is dealt with in a separate chapter, since they are of the greatest interest apart from the question of power-factor compensation. Speed regulation, and an extensive range of characteristics, enable them to be used in cases where no other form of motor is suitable.

Commutator Motors in Conjunction with Induction Motors.—The first idea of power-factor compensation by this means is due to Leblanc and Latour.

There is an advantage in using a commutator machine coupled to the rotor of the induction motor rather than a synchronous compensator coupled to the mains, because in the former case we are dealing with the slip frequency and in the latter case with the higher supply frequency.

This means a lower first cost, and lower losses, as will be shown subsequently.

Two cases may here be considered.

(1) It may be necessary, apart from compensation, to obtain an important speed drop at high loads (where a flywheel is used for peak loads, for instance).

In this case the commutator machine will have a stator winding and will act, as far as speed regulation is concerned, as a variable resistance in the induction motor-rotor circuit. *But the slip energy, instead of being lost in the form of heat, reappears as torque on the shaft.*

If the commutator machine is direct coupled to the end of the induction motor shaft, the torque will add itself to that of the induction motor, and the combination will give a constant torque whatever the speed may be. The commutator rotor may be said to represent a dynamic resistance, because the effect is identical to inserting a variable resistance in the rotor circuit, but no loss results.

It is particularly interesting to compare the two diagrams (Figs. 81 and 82) for the ordinary induction motor and for the combined group.

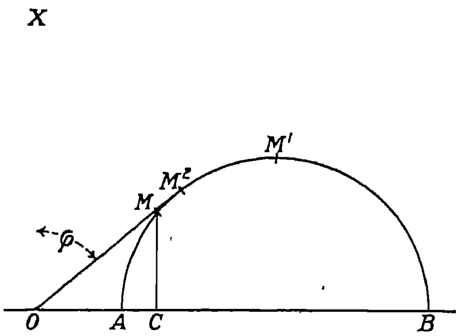


FIG. 81.—Diagram of ordinary induction motor.

The current will be given by OM, the torque by MC, and the power factor can be obtained from angle XOM. Under no-load conditions the running point will be at A; under full load it will be in the neighbourhood of M^2, OM^2 being the tangent to the circle (maximum power factor). Fig. 82 shows the diagram of the combined machines. Between no load and full load, the point moves from A to M^2. The power factor remains approximately equal to unity from 25 per cent. load onwards, and, moreover, it will be seen that it becomes a leading power factor between 50 per cent. load and full load (see also Fig. 85).

(2) Compensation alone is required, without any modification of the induction motor speed characteristic.

In this case several combinations may be considered :—

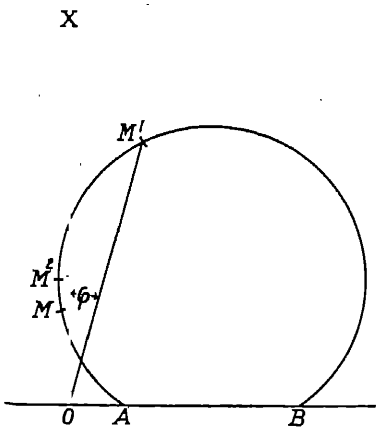


FIG. 82.—Diagram of combined induction and commutator motor (Cascade).

(*a*) The Leblanc-Latour exciter.
(*b*) The series commutator exciter.
(*c*) Auto-compensated induction motor.
(*d*) Frequency converter.

(a) **Leblanc-Latour Exciter.**—The arrangement is shown in Fig. 83, and the exciter consists of a commutator rotor in a

laminated iron ring with no winding. The commutator rotor is here driven at a speed much above that of the rotating field, and acts therefore as a negative reactance. Under such conditions the electromotive force developed in the exciter rotor is leading the current flowing through the winding, and the exciter produces wattless current which compensates that absorbed by the stator from the mains.

(b) **Series Commutator Exciter.**—The series exciter is a commutator machine provided with a stator winding and

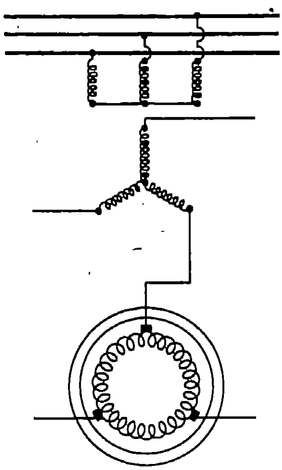


FIG. 83.—Leblanc exciter.

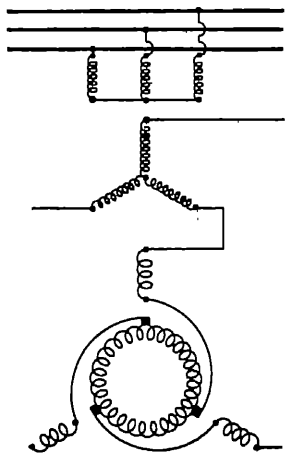


FIG. 84.—Series-commutator exciter.

brushes, which may be shifted to any required position. It is, in fact, a polyphase commutator motor identical to that referred to a little way back. The arrangement is shown in Fig. 84.

Compensation may be adjusted by altering the setting of the brushes.

Fig. 85 shows the diagram of such a machine expressed with kw. as abscissæ and reactive k.v.a. as ordinates. The curve passes through a point A such that OA represents the wattless component of the motor excitation, and through a point B which corresponds to approximately one-quarter of normal power.

The following conditions may therefore be obtained by means of such a combination :—

Load.	Cos . ϕ.
0	Lagging.
25-30 per cent.	Unity.
Above 30 per cent.	Leading.
100 per cent.	Unity or leading, according to brush-setting.

By shifting the brushes, any of the various characteristics shown in Fig. 85 may be obtained. The torque of the combination will be slightly better than for the induction motor alone.

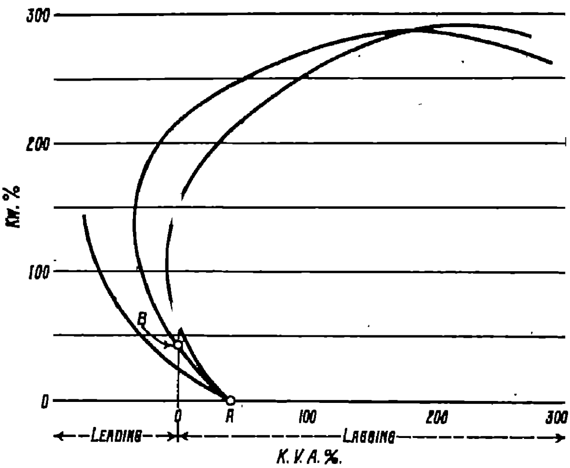


FIG. 85.—Diagram of series-commutator exciter expressed with kw. as abscissae and reactive k.v.a. as ordinates.

(c) **Auto-compensated Induction Motor.**—This type of machine is approximately the same size as an ordinary induction motor of similar rating. Both stator and rotor carry the usual polyphase windings. Compensation is obtained by means of a commutator provided with three rows of brushes. The commutator segments are connected to a closed winding of the direct-current type placed in the same slots as the main rotor winding. The rotor is thus provided, on the one hand, with three slip-rings connected to an ordinary polyphase winding, and on the other hand, with a commutator connected to a closed winding. The three slip-rings are connected to the supply

mains, and the three lines of brushes to the stator polyphase winding. Other combinations are, of course, possible, and a number of types of motors have been devised by altering the above-mentioned connections. The main principle, however, remains the same in all cases.

The commutator exciter is thus a part of the induction motor itself, and by this means a very compact design may be obtained.

The motor starts up on resistances just like an ordinary induction motor; in the case of very small motors, the rheostat may be omitted. In some cases a reactance coil is inserted between the slip-rings. On starting up, the frequency being that of the mains, the current is considerably reduced by the presence of these coils, and as the motor speeds up and the frequency drops, the limiting effect of the reactance coils drops also. This method is undesirable, because it reduces the starting torque and efficiency, and lowers the power factor.

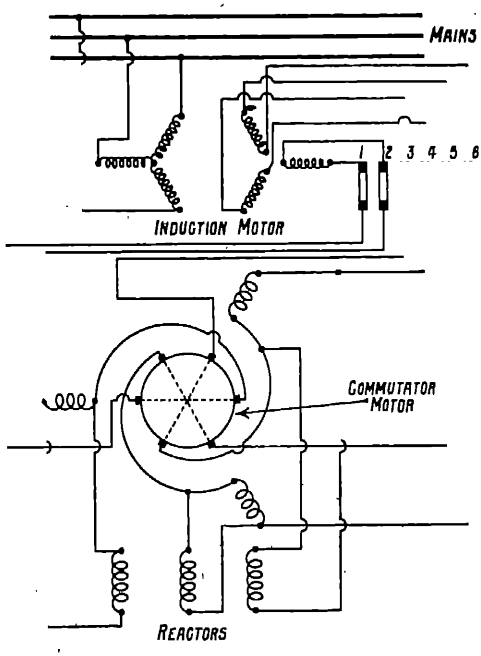


FIG. 86.—Combined induction and commutator motor.

By altering the setting of the brushes any required degree of compensation can be obtained, as would be the case for a separate commutator exciter and induction motor. A typical example of the auto-compensated induction motor is shown in Fig. 87. The General Electric Co. has recently developed a compensated induction motor known as the Witton All Watt

motor, which has all the characteristics of the ordinary slip-ring induction motor, with the exception that the power factor over the normal range is approximately unity.

This result is obtained by incorporating in the ordinary motor an exciting device consisting of a commutator connected to a low voltage winding similar to the exciter armature of a synchronous machine.

The stator A, rotor winding B, and slip-rings C are identical in every way with the corresponding parts of an induction motor. The rotor can be connected to either starting resistances D, or when these have been cut out, to the compensator E. This compensator is really a phase advancer, built into the machine, and

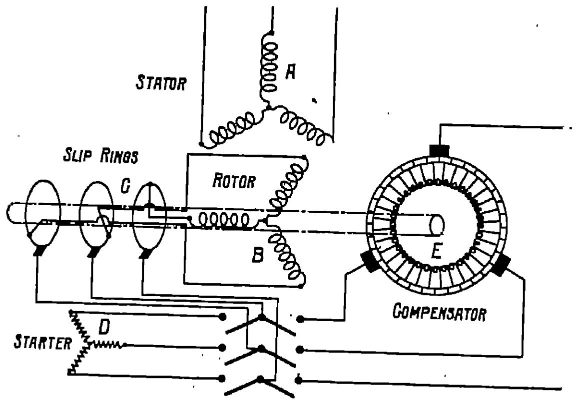


FIG. 87.—Compensated induction motor (General Electric Company).

its winding consists of a few turns of heavy gauge. When the machine has reached full speed, the compensating device and commutator are automatically switched in by moving the starting switch to the final position.

(d) **Frequency Converter.**—When the auto-compensated induction motor can no longer be used (high-voltage motors) the same characteristics may be obtained by cascading with the rotor a three-phase commutator machine with a non-wound stator, and excited by means of a small transformer supplied from the mains.

Compensation may also be obtained by means of a separate motor-generator set, one machine being an ordinary induction

motor supplied from the mains, the other a series exciter or an exciter of the Leblanc type.

Before passing to the analytical study of the induction motor, commutator motor combination, we may sum up the various methods we have briefly described and consider which type is most suitable for a given case.

Comparison between the Various Methods.—(*a*) *The motor is always running under nearly full load.*—In such a case, the disadvantage of the Leblanc or series exciter, which is that they do not feed back wattless current at no load, disappears entirely. The series exciter will be generally used as the degree of compensation may be easily adjusted.

(*b*) *The motor runs under a very variable load.*—If at minimum load there is still a load equal to about one-quarter of full load, the series exciter is still satisfactory. If, on the other hand, the minimum load is very low, say one-tenth of full load, then auto-compensated induction motors will be best.

PART II.—ANALYTICAL STUDY OF THE INDUCTION MOTOR AND COMMUTATOR MOTOR COMBINATION.

Preliminary Remarks: (1) **Magnetisation.**—In order to maintain the field in an induction motor, a certain definite number of ampere turns is necessary. The current flowing in the stator and rotor are such that their resultant suffices for the excitation. The rotating field produced induces an E.M.F. in the windings lagging by $\frac{\pi}{2}$.

The resultant excitation current being practically in phase with the field, the energy necessary for magnetisation is equal to the product of the E.M.F. by the excitation current, and if, as is the case for ordinary asynchronous machines, the excitation current flows in the primary winding, the magnetising energy must be drawn from the mains.

This is due merely to the particular conditions that are usually adopted.

It does not, in fact, matter whether the non-compensated ampere turns flow in the primary or the secondary. It is far better to feed the excitation current to the secondary winding, since the E.M.F. induced is only a small percentage of the

primary voltage. It follows that the necessary magnetising energy will be much less than would be necessary if the machine were excited through the primary winding. It was proposed at first to insert capacity in the rotors, but this was found to be unsound from a practical point of view.

Maurice Leblanc was the first to use a commutator rotor which, when rotating faster than its own rotating field, produces a voltage that leads the resultant flux by $\frac{\pi}{2}$, and acts therefore as would a condenser or negative reactance.

(2) **Characteristic Features of a Commutator Rotor Fed from a Polyphase Alternating Current Supply.**—Let us consider the case of a commutator rotor provided with three rows of

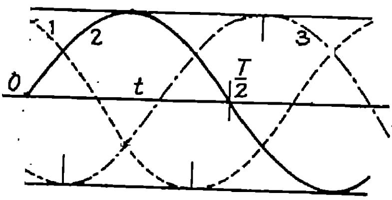


FIG. 88.—Commutator rotor with brushes 120° apart on three-phase system.

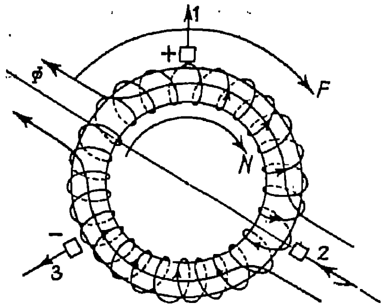


FIG. 89.—Schematic representation of motor with three brushes 120° apart on three-phase system.

brushes 120° apart, and a three-phase system as shown (Fig. 89). Let the brushes be numbered 1, 2, 3, these numbers corresponding to the sine curves of Fig. 88.

We know that a rotating field will be produced moving from the leading to the lagging phase. If we assume that the rotor revolves in the same direction as the field, at a speed greater than that of the field, then, at the instant when the current is maximum (2), the current in phase 1-3 of the rotor (Fig. 89) is zero, the flux being in the direction Φ, and the E.M.F. in 1-3 is at a maximum. The fundamental property of a commutator rotor is therefore to produce a voltage leading the resultant flux by 90°, when the rotor and the field are revolving in the same direction.

If we reverse the rotor, the voltage across 1-3 will also be reversed, and the E.M.F. in quadrature with the flux will now be a lagging one. The same result may be obtained if, instead of reversing the rotor, we reverse the field.

(3) **Self-induction Coefficient of the Exciter.**—Let the reactance of the windings be

$$aL_s \text{ and } aL_r,$$

aL_s being equal to the ratio $\frac{E_s}{I_{os}}$ where E_s is the electromotive force induced in the stator when a current I_{os} is flowing through it; and $aL_r = \frac{E_r}{I_{or}}$ in a similar manner.

The ratio of the reactances will be

$$\frac{aL_s}{aL_r} = \beta^2 \frac{\mu_s}{\mu_r},$$

where μ_s and μ_r are leakage coefficients for the stator and rotor. β may be defined either as the ratio of the coefficients by which the currents should be multiplied to obtain the ratio of magnetomotive forces, or as the ratio of the coefficients by which the flux per pole should be multiplied to obtain the ratio of the electromotive forces. These two definitions are, of course, equivalent for an equal number of phases in both rotor and stator, when the currents and electromotive forces are assumed to be sinusoidal. Otherwise, the two ratios would be different, and β^2 would become $\beta\beta'$.

It should be noted that aL_s and aL_r are variable according to the saturation, and therefore according to the setting of the brushes, and this will have to be taken into account when the method of calculation we are going to use is to be applied to a point which corresponds to a saturated region on the permeability curve of the machine.

Let us calculate β according to the first definition. We will consider a three-phase machine (Fig. 90), the stator and rotor of which are traversed by the same current, I. The maximum value of the rotating magnetomotive force expressed in stator ampere turns will be

$$ni_s = \frac{1}{3}\, 1{\cdot}5\, \frac{4}{\pi}\, k_1\, k_2\, \frac{N_s}{2p}\, I\sqrt{2}.$$

N_s is the number of effective stator conductors, K_1 Blondel's coefficient, which is equal to

$$\frac{\sin n\frac{\alpha}{2}}{n \sin \frac{\alpha}{2}}$$

where n is the number of slots per pole and per phase, and α the phase angle in space of the various component sine curves.

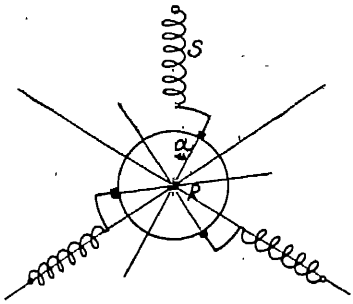


FIG. 90.—Schematic three-phase machine.

k_2 is equal to $\frac{\gamma}{2}$ where γ is the angle embraced by a turn of the winding. The maximum value of the rotating magnetomotive force for the rotor will be

$$ni_r = \frac{3}{2}\frac{4}{\pi}\frac{1}{3}\frac{N_r}{2}\frac{1}{p}\frac{1}{a}k_1'\ k_2'\ I\ \frac{\sqrt{2}}{\sqrt{3}}.$$

Hence the ratio will be

$$\beta = \frac{k_1 k_2 N_s a \sqrt{3}}{k_1' k_2' N_r}.$$

Let us now calculate the value of β starting from the second definition, and show that the two values are the same.

The electromotive force of the stator per phase can be written

$$E_s = \frac{1}{\sqrt{2}}\omega\frac{N}{6}\phi k_1 k_2 10^{-8} \text{ volts,}$$

and the radial electromotive force of the rotor will be

$$E_r = \frac{1}{2\sqrt{2}}\frac{N_r}{a}n\phi k_2' 10^{-8} \text{ volts.}$$

Hence the ratio

$$\beta = \frac{E_s}{E_r} = \frac{2\pi}{3}\frac{N_s}{N_r}\frac{k_1 k_2 a}{k_2'}.$$

It will be seen that these two values are identical, since

$$\frac{2\pi}{3} = \frac{\sqrt{3}}{k_1'} \qquad k_1' = 0{\cdot}83.$$

For a machine with three split phases (Fig. 91), we will have

$$\beta = \frac{N_s}{N_r}\frac{k_2}{k_2'}\frac{k_1}{k_1'}a = \frac{\pi}{3}\frac{N_s}{N_r}\frac{k_2}{k_2'}k_1 a.$$

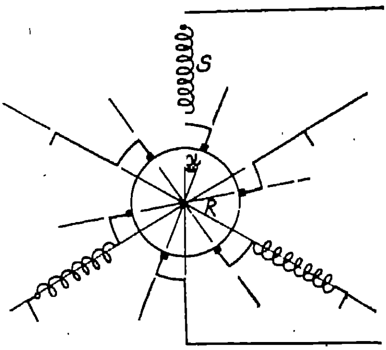


FIG. 91.—Schematic machine with three split phases.

Analytical Equations of the Induction Motor Commutator-motor Set.—Let—

U be the voltage per phase at the induction motor stator terminals.
I_s the primary current.
I_r the rotor current.
R_1 the resistance per phase of the stator.
R_2 the resistance per phase of the rotor.
L_1 the self-induction coefficient of the stator.
L_2 the self-induction coefficient of the rotor.
M_a the mutual induction coefficient between rotor and stator.
z the impedance $(R + aX) + ja\gamma$ of the commutator machine.
g the slip of the induction motor (see Fig. 92).

The voltage at the induction motor terminals will be

$$U = (R_1 + jaL_1)I_s + jaM_aI_r \quad . \quad . \quad (1)$$

whereas for the rotor we have

$$O = [R_2 + R + agX + jag(L_2 + \gamma)]I_r + jagM_aI_s \quad . \quad (2)$$

Let us express the impedance of the commutator machine, $z = (R + aX) + ja\gamma$ as a function of the various coefficients and the slip.

Let R_s be the resistance per phase of the exciter stator.

R_r the resistance of the rotor (reduced to equivalent star).

L_s self-induction coefficient of exciter stator..

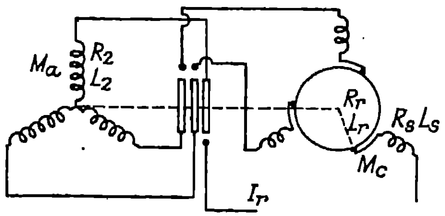


FIG. 92.—Commutator motor-induction motor combination.

L_r self-induction coefficient of exciter rotor (reduced to equivalent star).

M_o mutual induction coefficient.

k the brush-setting coefficient, $\cos\alpha + j\sin\alpha$.

g_o the commutator machine slip.

Then, if the commutator machine is fed with a constant voltage U, the voltage u_s and u_r at the stator and rotor terminals respectively will be—

$$u_s = (R_s + jaL_s - kjaM_o)I_r,$$
$$u_r = \left(R_r + jag_oL_r - \frac{1}{k}jag_oM_o\right)I_r,$$

whence the impedance

$$Z = \frac{U}{I_r} = \frac{u_s + u_r}{I_r}$$
$$= R_s + R_r + j\left[(aL_s - kaM_o) + g_o\left(aL_r - \frac{1}{k}aM_o\right)\right] \quad (3)$$

Identifying this expression with

$$z = (R + aX) + ja\gamma$$

we will get

$$(R + aX) = aM_o(1 - g_o)\sin\alpha + R_s + R_r$$
$$a\gamma = aL_s + g_oaL_r - aM_c(1 + g_o)\cos\alpha,$$

so that equation (2) becomes

$$O = (R_2 + R_s + R_r) + agM_o(1 - g_c)\sin\alpha + jag[(L_2 + L_s + g_oL_r) - M_o(1 + g_o)\cos\alpha]I_r + jagM_aI_s \quad (4)$$

The induction motor voltage, on the other hand, can be written

$$U_2 = (R_2 + jagL_2)I_r + jagM_aI_s.$$

The exciter rotor voltage, which is equal to it, may be written

$$U_2 = \{(R_s + R_r + gaM_o(1 - g_o)\sin\alpha + jg[aL_s + g_o(aL_r - aM_o\cos\alpha) - aM_o\cos\alpha])\}I_r \quad (5)$$

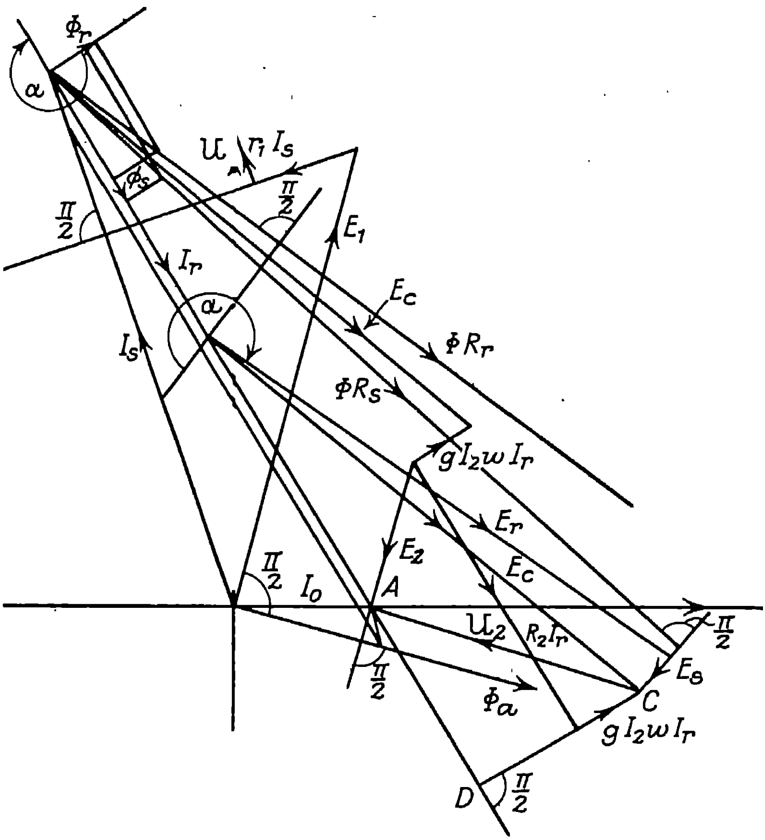


FIG. 93.—Classical diagram resulting from the vectorial composition of the fluxes applied to the induction motor-commutator motor set.

It will be noticed that this is composed of two parts, one in phase with I_r,

$$[R_s + R_r + gaM_o(1 - g_o)\sin\alpha]I_r,$$

and one in quadrature,

$$jgI_r[aL_s + g_o(aL_r - aM_o \cos \alpha) - aM_o \cos \alpha].$$

Fig. 93 gives the classical diagram which results from the vectorial composition of the fluxes applied to the induction motor-commutator motor set. We find in AC the common voltage U_2, and in AD and CD the two components whose equations we have just written—

$$AD = [R_s + R_r + gaM_o(1 - g_o) \sin \alpha]I_r$$

and

$$DC = jgI_r[aL_s + g_o(aL_r - aM_o \cos \alpha) - aM_o \cos \alpha].$$

Practical Method for Determination of Exciter.—In practice, the data for the problem are as follows.

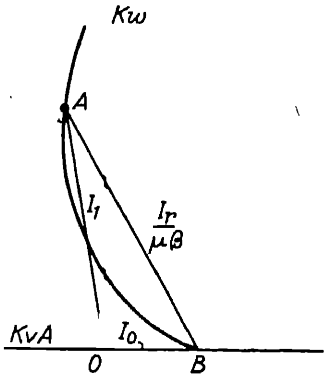


FIG. 94.—Circle diagram.

We are given the load-curve which it is desired to obtain,

$$kw = f(\text{KVA}).$$

We must determine L_s, L_r, and M_o at various points on the curve and find whether it is possible, for a given setting of the brushes, to place these various values on a common magnetisation curve.

Equations (1) and (2) enable us to write (neglecting the resistance R_1 of the motor stator and using the notation,

$$R_2 + R_3 + R_r = R_t)$$

$$Z = jaL_1 + \frac{a^2M_a^2}{\frac{R_t}{g} + a\chi + j(aL_2 + a\gamma)} \quad . \quad . \quad (6)$$

which will give us the impedance diagram of the set. The diagram, as will be seen, is a circle, the denominator being linear as regards $\frac{1}{g}$. Generally, we may take as a first approximation $R_s + R_r = {}^1/_5\, R_2$, plus the contact resistance of the brushes and

the resistance of the connectors, assuming 0·8 volt as the value of the voltage drop per brush on the commutator, 0·2 volt per brush on the slip-rings, and 0·5 volt in the connectors at normal load.

Let us try and obtain simple expressions for β and aL_1 for a point on the load curve.

By identifying (6) with

$$Z = \frac{E}{I_w + jI_d}$$

where I_w and I_d are the energy and reactive components of the current, we get

$$a\chi = \frac{a^2 M_a{}^2 E\frac{I_w}{I^2}}{\left(E\frac{I_w}{I^2}\right)^2 + \left(E\frac{I_d}{I^2} + aL_1\right)^2} - \frac{R}{g},$$

$$a\gamma = a^2 M_a{}^2 \frac{E\frac{I_d}{I^2} + aL_1}{\left(E\frac{I_w}{I^2}\right)^2 + \left(E\frac{I_d}{I^2} + aL_1\right)^2} - aL_2,$$

with $I^2 = I_w{}^2 + I_d{}^2$,
but

$$a\chi = aM_0(1 - g_0) \sin \alpha$$

and

$$a\gamma = aL_s + g_0 aL_r - aM_0(1 + g_0) \cos \alpha.$$

Now, expressing the induction coefficients of the commutator machine in function of β, we get

$$aM_0 = \frac{aL_s}{\beta\mu_1} \qquad aL_r = \frac{aM_0\mu^2}{\beta} = \frac{aL_s}{\beta^2}\frac{\mu_2}{\mu_1} =/=/= \frac{aL_s}{\beta^2}.$$

μ_2 and μ_1 are approximately equal, and hence $a\chi$ and $a\gamma$ become

$$a\chi = \frac{aL_s}{\beta\mu}(1 - g_0) \sin \alpha,$$

$$a\gamma = aL_s + g_0\frac{aL_s}{\beta^2}\frac{\mu_2}{\mu_1} - \frac{aL_s}{\beta\mu_1}(1 + g_0) \cos \alpha,$$

whence we get

$$\beta = \frac{a\chi\frac{1+g_0}{1-g_0}\frac{\cos\alpha}{\sin\alpha} + a\gamma \pm \sqrt{\left[a\chi\frac{1+g_0}{1-g_0}\frac{\cos\alpha}{\sin\alpha} + a\gamma\right]^2 - \frac{4g_0(a\chi\mu)^2}{[(1-g_0)\sin\alpha]^2}}}{\frac{2a\chi\mu}{(1-g_0)\sin\alpha}} \quad (7)$$

and $$aL_s = \frac{a\chi\mu}{(1-g_0)\sin\alpha} \quad . \quad . \quad . \quad (8)$$

If we assume a brush setting of 270°, the above expressions become

$$\beta = \frac{a\gamma(g_0 - 1) \pm \sqrt{[a\gamma(1-g_0)]^2 - 4g_0(a\chi\mu)^2}}{2a\chi\mu}$$

and $$aL_s = \frac{a\chi\mu}{g_0 - 1}.$$

Considering only one of the two solutions, the denominator of β is negative, since $a\chi = aM_0(g_0 - 1)$ and g_0 is negative. Therefore the numerator must also be negative, since β must be positive.

$$a\gamma(g_0 - 1) = (aL_s + g_0 aL_r)(g_0 - 1)$$

is always positive. Therefore the only solution that will be acceptable is that with the negative sign before the radical, the latter being in absolute value greater than $a\gamma(g_0 - 1)$, β will be smaller than unity if

$$a\gamma(g_0 - 1) - \sqrt{[a\gamma(g_0 - 1)]^2 - 4g_0(a\chi\mu)^2} > 2a\chi\mu,$$

or, if $$-\mu(g_0 + 1) < -\frac{a\gamma}{a\chi}(g_0 - 1).$$

This will obviously be the case if

$$\mu < \frac{a\gamma}{a\chi}.$$

For a given point on the load curve, $a\chi$ varies with the slip, since it is an expression of the form $A - \frac{R}{g}$ whereas $a\gamma$ is independent.

It will be seen from this that for equal compensation β can vary between wide limits.

A similar calculation could be made for the case when the

commutator machine revolves in the opposite direction to the rotating field.

It should be noted that for equal outputs, the ratio of the slip as a compensated motor to the slip as an induction motor is given by the expression,

$$\frac{g'}{g} = R_t + \frac{a_1 a M_0 \sin \alpha}{R_2}\left(\frac{I_2'}{I_2}\right)^2.$$

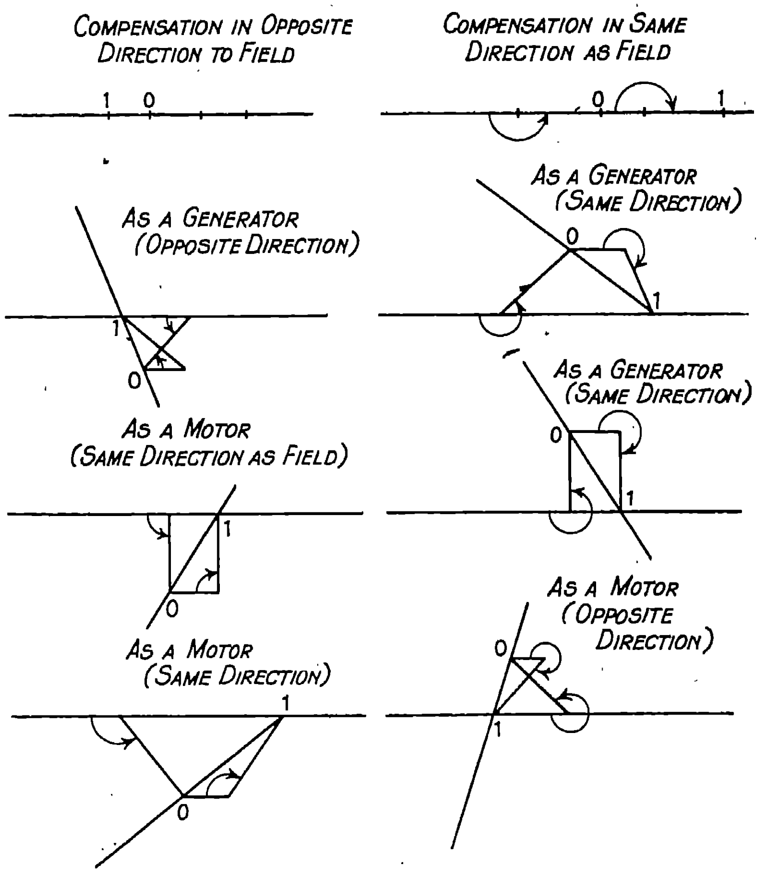


FIG. 95.—Diagrams for $\beta > 1$.

Considerations of slip aside, the compensation effect would be a maximum for 180°, but as the slip decreases as we approach $\frac{3\pi}{2}$, it will be seen that, for each machine an optimum setting

may be found near this value which will give maximum compensation compatible with minimum slip.

Figs. 95 and 96 bring out the possibilities of operation for

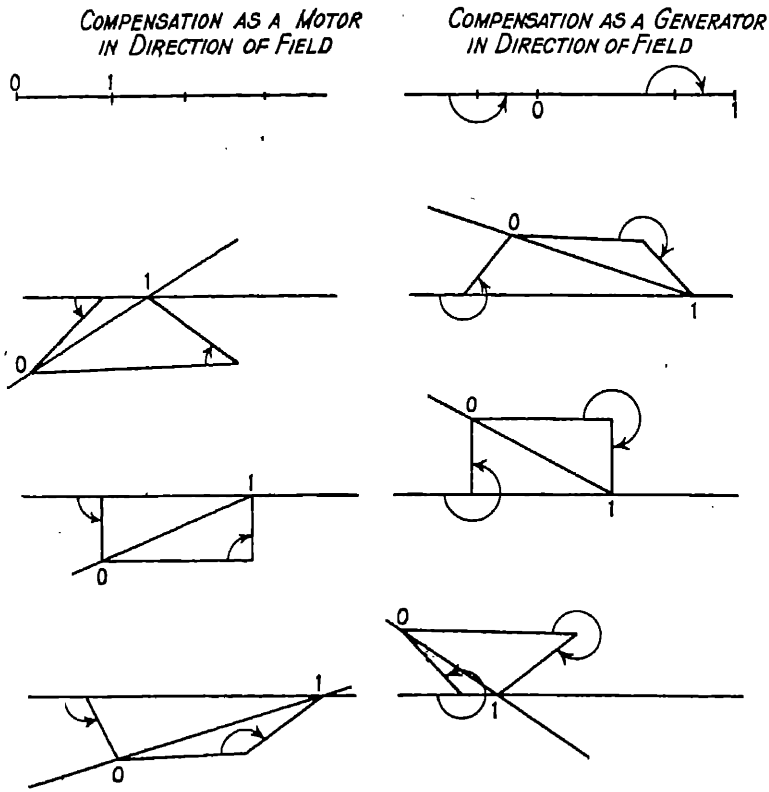


FIG. 96.—Diagrams for $\beta < 1$.

commutator polyphase machines with different transformer ratios.

We have seen how we may find the values of β and aL_s for any point on the load curve and a given slip. For other points, knowing β and α, we will calculate aL_s and g_o, g_o being a function of the induction motor slip g.

$$g_o = 1 + a_1 - \frac{a_1}{g},$$

when the commutator machine is rotating in the direction of the rotating field at the same speed as the induction motor, and $a_1 = \frac{p_o}{p_a}$, the ratio of the number of poles of the commutator machine and the induction motor.

The commutator-machine field rotates the more slowly, and the frequency in the rotor conductors is the greater, the greater the number of poles. The E.M.F. increases with the rotor frequency, and the machine will be the more efficient as the ratio $a_1 = \frac{p_o}{p_a}$ becomes greater.

There is a limiting factor due to losses in the iron, which increase as the square of the frequency.

If f is the supply frequency, the speed of the induction motor at synchronism is $n_a = \frac{f}{p_a}$, and that of the commutator machine $n_s = \frac{gf}{p_o}$, g being the slip of the induction motor. If we take the supply frequency as a limit for the frequency in the commutator machine, we have

$$p_o n_a \leq f, \qquad \text{or } \frac{p_o}{p_a} f \leq f, \qquad \text{or } \frac{p_o}{p_a} \leq 1.$$

Practically, a_1 will be between 0 and 1, but it is more

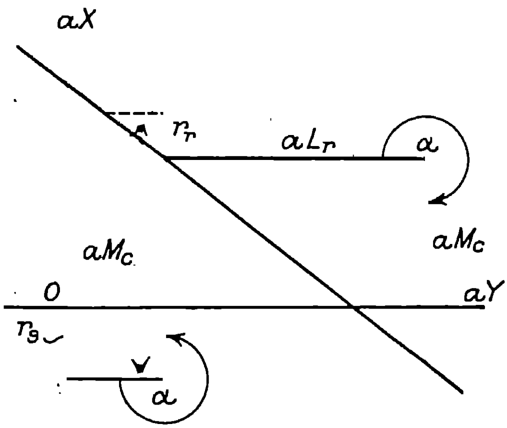


FIG. 97.—Diagram of commutator machine for bush setting of 270°.

advantageous, as far as compensation is concerned, to keep a_1 in the neighbourhood of unity. To understand this clearly,

let us consider the diagram of the commutator machine (Fig. 97) for a brush setting of 270° for instance. Turning to equation (3) we find that the magnetising energy will be the greater, the greater the slip g_o. But g_o will be the greater itself, for a given value of the induction motor slip, the nearer a_1 is to unity.

From the above equations, for any point of the load curve we get

$$g = \frac{B \pm \sqrt{B^2 - 4CD}}{D} \quad . \quad . \quad . \quad (9)$$

and

$$aL_s = \frac{a\chi\beta\mu}{g_o - 1} \quad . \quad . \quad . \quad . \quad (10)$$

and, in the most general case,

$$A = \frac{a^2 M_a{}^2 E \frac{I_w}{I^2}}{\left(E\frac{I_w}{I^2}\right)^2 + \left(E\frac{I_d}{I^2} + aL_1\right)^2}.$$

$$B = \mu(R\beta^2 + Aa_1 + R + a_1R) + a\gamma\beta a_1 \sin\alpha - \cos\alpha(\beta a_1 A + 2R\beta + \beta R a_1).$$

$$C = a_1 R(\mu - \beta\cos\alpha).$$

$$D = A\mu(\beta^2 + 1 + a_1) - A\beta\cos\alpha(2 + a_1) + \beta a\gamma a_1 \sin\alpha.$$

These equations are much simplified for an angle of 270° and become

$$B = \mu(R\beta^2 + Aa_1 + R + a_1R) - a\gamma\beta a_1.$$

$$C = a_1 R\mu.$$

$$D = A\mu(\beta^2 + 1 + a_1) - \beta a\gamma a_1.$$

Hence, for any given setting of the brushes we obtain a series of values for aL_s and g, each of which corresponds to a different load, and therefore to different values of the current in the commutator machine. It will be easy to see, therefore, that it will be possible so to design the machine as to obtain such a magnetising curve. From the diagram we can obtain the value of the rotor current I_r, remembering that $I_r = \sqrt{I_0{}^2 + I_s{}^2} \times$ loss coefficient of induction motor rotor $\times$ transformer ratio.

Equation (6) gives us, for each value of aL_s and every brush setting a circle, which is determined by three points :—

(*a*) No load,

$$z_0 = jaL_1.$$

(*b*) Starting,

$$Z_1 = jaL_1 + \frac{a^2M_a{}^2}{R_t + j(aL_2 + aL_s + aL_r - ZaM_0 \cos \alpha)}.$$

(*c*) Slip $= \infty$.

$$Z_\infty = jaL_1 + \frac{a^2M_a{}^2}{-aM_{a1} \sin a + j[aL_2 + aL_s + aL_r(1+a_1) - aM_0(Z+a_1) \cos a]}.$$

This will enable us to check the results obtained by means of equations (7), (8), (9), (10). The circles shown in Fig. 98

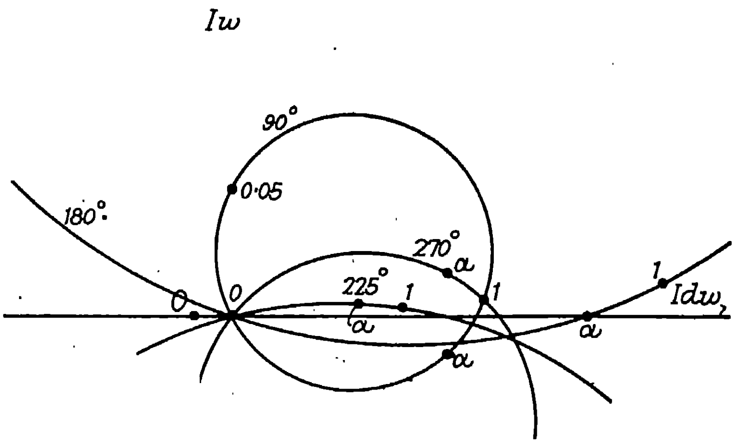


FIG. 98.—Circle diagrams of commutator motor corresponding to curves in charts 1-5.

correspond to the commutator machine, tests of which are shown in charts 1 to 5.

There are two possible cases, when the commutator rotor revolves in the same direction as the field or in the opposite direction.

The equations established in the preceding pages bring out the two methods of operation, the rotor revolving in the same direction as the rotating field, or in the opposite direction. The first case alone has been examined, and leads to a brush setting of 240°, or thereabouts, in advance of the neutral line.

The second case gives similar results for a lagging brush setting of about 60°.

Whereas in the first case the slip of the commutator machine is

$$g_0 = 1 + a_1 - \frac{a_1}{g}$$

in the second case, it becomes

$$g_0 = 1 - a_1 + \frac{a_1}{g}.$$

The impedance of the combination, in both cases, for $g = 0$ will be

$$Z_0 = Z_0' = jaL_1$$

for $g = \infty$.

$$Z_\infty = jaL_1 + \frac{a^2M_a^2}{-a_1aM_a \sin . \alpha + j[aL_2 + aL_s - aM_a \cos \alpha(Z + a_1) + (1 + a_1)aL_r]}$$

and

$$Z'_\infty = jaL_1 + \frac{a^2M_a^2}{a_1aM_a \sin \alpha + j[aL_2 + aL_s - aM_a \cos \alpha(Z - a_1) + (1 - a_1)aL_r]}$$

for $g = 1$.

$$Z_1 = Z_1' = jaL_1 + \frac{a^2M_a^2}{R_t + j(aL_2 + aL_s + aL_r - ZaM_a \cos \alpha)}.$$

The second case disappears as soon as $\beta \angle 1$. In this case, of course, compensation can only be possible if the rotor revolves in the same direction as the field.

Auto-excitation of the Commutator Machine.—A curious phenomenon occurs when the brushes are set past the neutral line in the opposite direction to that of rotation.

Let us consider the most general case of a machine with separate phases, and three fixed brushes and three movable ones, the current increasing with γ passing through a maximum, and falling to zero again for 180°.

In the position which corresponds to the neutral line, the stator magnetomotive forces and those of the rotor may be arithmetically summed. For a brush-setting α from the neutral line, the number of active rotor conductors becomes

$$N_2 = N \cos . \frac{\alpha}{2},$$

where N is the total number of conductors.

In Figs. 99 and 100 we have assumed that the current reaches a maximum in the phase shown, so that the other two merely help that one on. The direction of the torque is clearly shown in both cases. Fig. 99 corresponds to the case when the motor is rotating in the same direction as the field, whereas in Fig. 100 it is rotating in the opposite direction. Under certain conditions the machine can generate polyphase currents even when it is unconnected to any supply, the frequency of these currents depending on the brush setting.

It will be easily seen that Figs. 99 and 100 may be considered as representing series direct-current machines; the black and

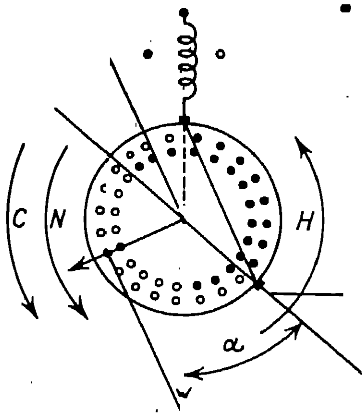


FIG. 99.—Auto-excitation motor rotating in same direction as field.

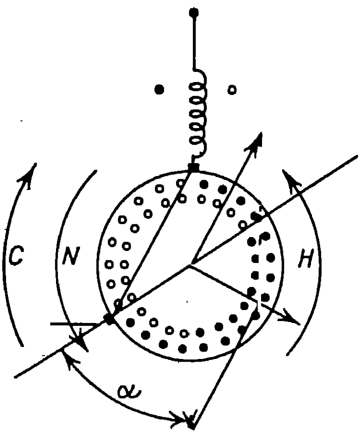


FIG. 100.—Auto-excitation motor rotating in opposite direction to field.

white circles showing the direction of the current in the conductors. In Fig. 99 the machine would demagnetise itself, and auto-excitation could not take place. The opposite will be the case for Fig. 100.

The limit resistance for auto-excitation in the case of the characteristic given (Fig. 101) would be

$$R_0 = \frac{E_0}{I_0} = tg \, . \, \phi_0 .$$

The form of this curve depends on the speed, and on the brush-setting, the active rotor conductors being $N_2 = N \cos \frac{\alpha}{2}$.

The rotor E.M.F. may be written approximately as

$$E_2 = K_1 n\phi N_2 = K_2 n I N^2 \sin . \frac{\alpha}{2} \cos \frac{\alpha}{2}$$
$$= K_3 n I \sin \gamma$$

$(\gamma = 180^\circ - \alpha)$.

Hence the limiting resistance,

$$R_0 = K_3 n \sin \gamma.$$

In the case of a three-phase machine the expression will be of the form,

$$R_0 = \frac{K}{e} N_s N_r n \frac{S}{K_e} K_1 K_2,$$

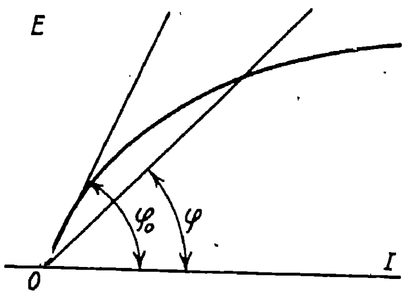


FIG. 101.—Characteristic showing limit resistance for auto-excitation.

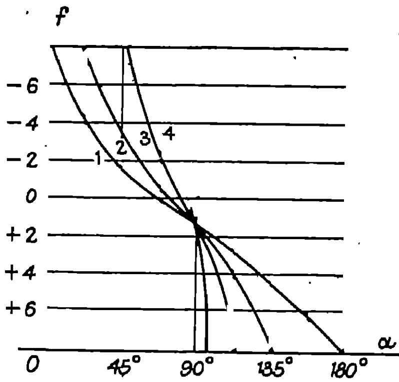


FIG. 102.—Auto-excitation conditions for a three-phase series commutator machine.

assuming the brushes set at an angle of $\frac{\pi}{2}$ lagging with regard to the neutral line and the direction of rotation.

N_s and N_r are the effective stator and rotor conductors, n the speed, e the air-gap, S the air-gap surface, K_e the air-gap coefficient, K_1 and K_2 the reduction coefficients depending on the winding.

If the machine is connected to three resistances whose value is smaller than R_0, then, for a given brush-setting, a current will flow in two phases until the third excites itself, and hence by reaction, polyphase currents start up in the three

phases. Fig. 102 sums up the auto-excitation conditions for a three-phase series commutator machine.

The frequency is plotted as a function of the brush-setting. Curves 1, 2, 3, and 4 correspond to increasing external resistances. Positive frequencies correspond to one direction of rotation of the field, negative frequencies to the other.

If we suppose the machine connected to an impedance $R + jaX$, then, from former equations, we may write

$$R + r + aM_0(1 - g_0)\sin\alpha = 0$$
$$X + L_s + gL_rM_0(1 + g_c)\cos\alpha = 0.$$

Introducing the frequency f and the speed n, we get

$$tg\,.\,\alpha = \frac{R + r}{2\pi pn} \times \frac{f - pn}{(X + L_s)f + (f - pn)L_r},$$

so that for an angle,

$$tg\,.\,a = \frac{R + r}{L_r 2\pi pn}.$$

Auto-excitation as a direct-current machine will take place.

This has been verified at the Jeumont works on a four-pole machine for which the coefficient aL_r was 0·137 ohm for 33 cycles. With a resistance $R + r$, in circuit equal to 0·18 ohm, auto-excitation in direct current occurred at 1000 r.p.m. for an angle of $\alpha = 50°$. The above formula would give

$$tg\,.\,\alpha = \frac{0{\cdot}18}{0{\cdot}00066 \times 2 \times 3{\cdot}14 \times 2 \times \frac{1000}{60}} = 1{\cdot}3. \qquad \alpha = 52{\cdot}5°.$$

R was varied within wide limits, and it was shown that the formula gives correct results.

The Leblanc Exciter.—Some mention has been made at the beginning of this chapter of the Leblanc exciter, which first gave rise to the induction motor-commutator motor combination. We have seen that this machine differs from an ordinary commutator machine in that the stator is not wound, and is merely a laminated iron ring.

Let L_1, L_2, and L_r be the self-induction coefficients of the motor and exciter, R_1, R_2, R_r the resistances. We may write for the stator,

$$U_1 = (R_1 + jaL_1)I_s + jaMI_r \quad . \quad . \quad (1)$$

and for the rotor,

$$O = jgaMI_s + (R + jgaL_2 + jgagg_oL_r)I_r \quad . \quad (2)$$

R being the total resistance, that is, one phase of the induction motor stator + contact resistance of two brushes (slip-ring and commutator) + exciter rotor resistance (reduced to equivalent star).

From (1) and (2) we get

$$Z = R_1 + jaL_s + \frac{a^2M^2}{\frac{R}{g} + j(aL_2 + ag_oL_r)} \quad . \quad . \quad (3)$$

Identifying this with $Z = \dfrac{E}{I_w + jI_d}$

we get

$$\frac{R}{g} = \frac{a^2M^2\left(E\frac{I_w}{I^2} - R_1\right)}{\left(E\frac{I_w}{I^2} - R_1\right)^2 + \left(E\frac{I_d}{I^2} + aL_1\right)^2}$$

and

$$g_oaL_2 = a^2M^2\frac{E\frac{I_d}{I^2}aL_1}{\left(E\frac{I_w}{I^2} - R_1\right)^2 + \left(E\frac{I_d}{I^2} + aL_1\right)^2} - aL_2$$

if we neglect the resistance R_1 of the stator,

$$\frac{R}{g} = a^2M^2\frac{E\frac{I_w}{I^2}}{\left(E\frac{I_w}{I^2}\right)^2 + \left(E\frac{I_d}{I^2} + aL_1\right)^2}$$

and

$$g_oaL_2 = a^2M^2\frac{E\frac{I_d}{I^2}aL_1}{\left(E\frac{I_w}{I^2}\right)^2 + \left(E\frac{I_d}{I^2} + aL_1\right)^2} - aL_2.$$

The current in the rotor, I_r, which corresponds to the point on the load curve under consideration will be expressed by

$$\beta\mu\sqrt{(I_d + I_o)^2 + I_w^2},$$

where β is the transformer ratio of the induction motor,

$$\beta = \frac{k_1}{k_2}\frac{N_1}{N_2},$$

k_1 and k_2 are winding reduction coefficients.
N_1 = stator turns.
N_2 = rotor turns.

For each point of the curve, we thus get the slip g of the induction motor and the required coefficient L_r.

We know that in a closed winding comprising N effective conductors, the voltage across diametrically opposed brushes is

$$U = \frac{2}{\sqrt{2}}\frac{N}{2a}f\Phi k_r \mu 10^{-8} \text{ volts}$$

(f is the rotation frequency of the field with regard to the rotor, and $2a$ the number of winding paths).

Since $\Phi = \frac{2}{\pi}B_e \tau L$ where L = length of armature and τ the polar span, we will obtain Φ and B_e.

The necessary rotor ampere turns for this maximum value of the induction will be

$$AT = 2 \times 0{\cdot}8 e K_e B_e.$$

But for a three-phase rotor the rotor ampere turns per pair of poles are given by

$$AT = \frac{\sqrt{2}}{\pi}\frac{k_r k_r'}{p}\frac{I_r}{a\sqrt{3}},$$

from which we deduce the value of I_r necessary in order to obtain a given value for U, and hence aL_r.

Graphical Solution.—The problem may be solved graphically. Equation (2) can be written

$$\overline{U_b} + \overline{R_{ex}}\ \overline{I_r} + \overline{E_{ex}} = 0,$$

where U_b is the voltage at the induction motor terminals.

We know that E_{ex} is leading I_r by $\frac{\pi}{2}$, and we have a right-angled triangle with RI_r and E_{ex} as sides and U_b as hypothenuse. The problem consists of finding the exciter voltage when the

induction motor is known, and the load curve to be obtained also (Fig. 103).

Let A be a given point on load (corresponding to $\cos \phi = 1$, since the construction may be used for any point) (Fig. 103).

Take $OB = I_0$,

$$\text{we get} \quad AB = \frac{I_r}{\beta\mu}. \text{ and } \beta = \frac{K_1N_1}{K_2N_2}, \text{ and } AC = \frac{I_r}{\beta}.$$

The resultant stator flux is along OB (resultant of I_s and $\frac{I_r}{\beta\mu_2}$).

The rotor resultant flux is along OM (resultant of I_r and $\frac{I_s}{\mu_1}$).

$$ON = \frac{I_s}{\mu_1}, \qquad OA = I_s,$$

$$AB = \frac{I_r}{\beta\mu_2}, \qquad AC = \frac{I_r}{\beta}.$$

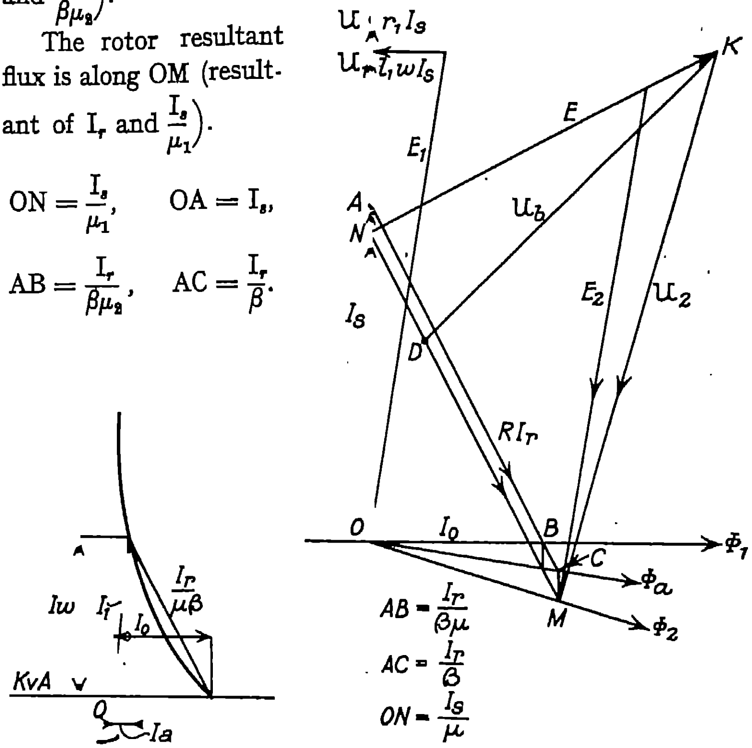


FIG. 103.—Graphical solution for exciter voltage when induction motor characteristics are known and required load-curve data.

Just as U_1 is leading Φ by $\frac{\pi}{2}$, so U_2 is lagging behind Φ_2 by $\frac{\pi}{2}$, and is therefore perpendicular to OM.

Drawing NK perpendicular to NM, NK will give us the

value of E_{ex} on the same scale as NM represents RI_r.

$$\overline{U_1} = \overline{U_{stator}} - \overline{R_1 I_s} \qquad \overline{U_2} = \overline{U_b} + \overline{R_{induction}\, I_r}.$$

All that is now necessary is to find the slip of the induction motor, which we must know in order to get the value of the frequency which the exciter should give to the voltage E_{ex}.

Let us consider the primary and secondary E.M.F.'s that correspond to the common flux, we have $E_2 = gE_1$,

whence $$g = \frac{E_2}{E_1},$$

and the exciter frequency $= f \times g \times g_o$, where f is the supply frequency.

DK represents both the voltage on the induction motor slip-rings, $\overline{U_b} = \overline{U_2} - \overline{R_a I_r}$, and the voltage on the exciter brushes,

$$\overline{U_b} = \overline{E} - \overline{R_{ex}\, I_r}.$$

Losses in the Combination.—The extra energy absorbed for compensation varies but little with the different systems used. The distribution of these losses alone varies.

Separate Auxiliary Motor-exciter Sets.—In the case where compensation is obtained by means of a separate set, the induction motor which drives the exciter must supply not only the exciter losses (friction, ventilation, iron and copper losses), but also a part of the Joule losses of the main motor, the amount of which will vary with the slip, and may amount to the total value of these losses for very small slips.

Generally speaking, the secondary losses are equal to the sum of the power absorbed by the auxiliary driving induction motor and the slip energy of the main motor.

The power absorbed by the auxiliary driving induction motor will be the higher the smaller the slip of the main motor.

The Machines are Coupled to a Common Shaft.—In this case, the power corresponding to the above losses is supplied by the main induction motor and transmitted mechanically through the shaft to the exciter.

In the case of a Leblanc exciter driven by an auxiliary motor, the Joule losses are entirely supplied by the main induction motor.

Test Results.—Twelve series of curves are given showing tests with—

(*a*) A commutator motor and induction motor coupled on the same shaft.

(*b*) An induction motor compensated by means of a separate induction motor-commutator motor set.

In all cases the transformer ratio for the exciters is > 1, and therefore they run both in the same direction as, and in the opposite direction to, the rotating field (see chart 1 to 5).

Practical Examples.

In concluding this exposition of the theory of the compensated induction motor, it is interesting to give two concrete examples showing the advantage of this means of compensation.

I. In the first example, the average power of the plant was 1500 kw. hours, the average power factor 0·69 to 0·70, which corresponds to a magnetising power of some 1550 k.v.a. hours.

According to the contract on which power was supplied, a penalty of 1 per cent. of the normal price of the kw.h. was due for each point the power factor dropped below 0·75.

The company paid out, therefore,

$$1500 \times 0{\cdot}23 \times 0{\cdot}05 = 17 \text{ francs } 20.$$

Two of the existing motors were then compensated, and the power factor brought up to the desired value. The extra power required for compensation amounted to 8 kw., which corresponded to an expense per hour of $0{\cdot}23 \times 8 = 1$ franc 80. The economy, therefore, was 17 francs 20 − 1 franc 80 $\doteq$ 15 francs 40 per hour

II. The second case is that of a smaller plant, the average power of which was about 240 kw.h. The average power factor was only 0·60 (small motors for individual drive).

A 50 h.p. compensated motor was installed and the power factor raised to 0·80.

The economy in this case was

$$240 \times 0{\cdot}25 \times 0{\cdot}20 = 12 \text{ francs an hour.}$$

Taking one penny a unit as the price of power for comparative purposes, on the 1500 kw.h. plant, the economy would have been 5s. 6d. per hour, and in the second case, 4s. per hour.

PART III.—DESCRIPTION OF VARIOUS COMPENSATED MOTORS.

The demand for a three-phase induction motor capable of supplying its own magnetising current, and thus running with a power factor in the neighbourhood of unity, has lately become very keen, and it has scarcely been possible for any electrical firm to avoid putting such a machine on the market.

The Witton All Watt motor, designed by the General Electric Company, has already been mentioned as a typical example of the auto-compensated induction motor, and it is now proposed to describe some of the more outstanding types.

Auto-compensated motors, that is, motors in which the induction and commutator portions have been incorporated in a single unit, are, of course, essentially small-power machines. But they are of very considerable interest in that it is precisely where a number of small motors are in use that the worst power factor conditions prevail.

The extra cost of installing motors of this type has, up to the present, very considerably limited their application.

Indeed, commutator motors have rarely been installed with a view to improving the power factor apart from all other considerations. They have been mainly used where accurate speed control was an essential operating feature. And yet, interesting though the speed control qualities of the commutator machine may be, perhaps power-factor improvement may be a more important quality still. This point, which is too often glossed over, we have tried to emphasise in the present chapter.

Since power-supply companies have started encouraging users with a high power factor by giving appropriate rebates and penalties, the question is becoming increasingly important, and as few plants can afford to set up either rotary converters or synchronous condensers solely for the purpose of improving the power factor, commutator motors, and commutator-compensated induction motors, must gradually come to the fore.

It will be found that the increased expense will be rapidly written off, and that such motors will pay for themselves in a surprisingly short time. Nor need there be any anxiety as regards commutation. Modern designs, and, above all, the choice of suitable brushes, has eliminated all trouble in this respect.

Originally the question of power factor was not a disturbing element, but, with the rapid growth of industrial load, the central stations have been confronted with a real problem in the diminishing power factor. The increasing power load with decreasing power factor involves very serious considerations. A considerable proportion of the power-station equipment is idle as far as any return on the investment is concerned, and the low power factor involves heavy operating losses as we have seen at the beginning of this chapter.

The great problem which the commutator motor and compensated induction motor have solved, is that of raising the power factor of the smaller individual industrial customer.

The Fynn-Weichsel Motor.—This motor starts as a slip-ring induction motor, having starting torque characteristics much more favourable than the usual squirrel-cage motor; that is, it will develop 150 per cent. torque with a starting current of from 150 to 200 per cent.

After the motor attains synchronism, which it will do easily with 150 per cent. load, it becomes a self-excited synchronous-induction motor. Over the normal load range, as shown in Fig. 104, the motor operates at leading power factor, thus providing compensation for the lagging current taken by other motors of induction type installed on the same line. As a synchronous-induction motor, it will carry 150 per cent. load without falling out of step. Above this value it drops into induction motor characteristics, and continues to run as a slip-ring motor to the breakdown point of approximately 300 per cent. load, when it stops.

The motor may be designed for a wide range of characteristics, particularly in respect to power factor at various loads. Fig. 104 shows operating results obtained with a motor designed to operate in parallel with induction motors for correction of low power factor.

It should be noted that with the windings provided the power factor of the motor at no-load is 65 per cent. leading, at one-half load 80 per cent. leading, at full load 92 per cent. leading, at one and one-half load the power factor is unity and the motor about to drop from synchronous to induction speed.

Loading the motor beyond the limits of synchronous speed operation simply establishes slip sufficient to carry the load as an induction motor. There is always a synchronising tendency that reduces slip, and when the load decreases to a point below

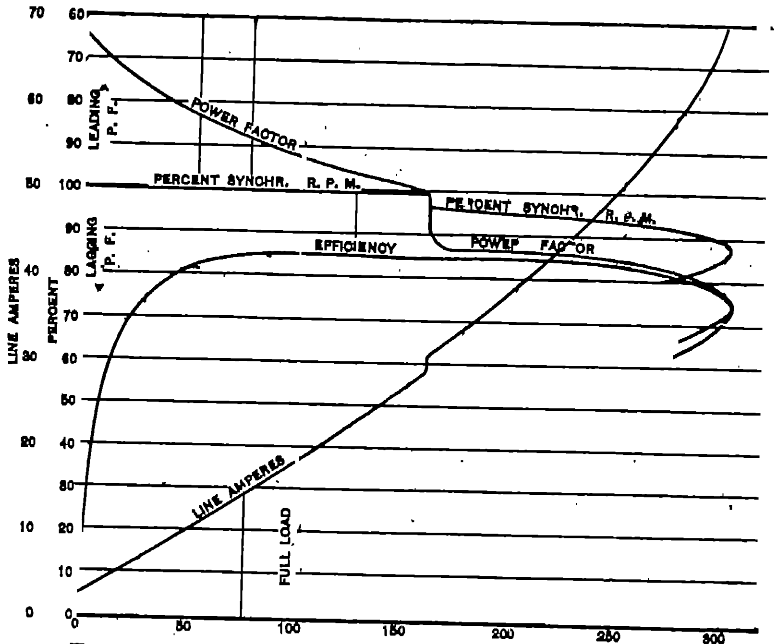


FIG. 104.—Characteristic curves of Fynn-Weichsel motor.

150 per cent. of full load, it pulls the rotor back into synchronism. The value of this characteristic is very great, as it enables the motor to carry temporary excess overloads in the same way that a squirrel-cage or slip-ring induction motor will carry overloads, thereby making the motor just as stable and practical in its operation as present types of induction motor.

Fig. 105 is interesting as showing the effect of operating two motors of the same size, one an ordinary slip-ring motor, the other the Fynn-Weichsel motor, in parallel on the same circuit.

In the diagram the lower of the two power-factor curves is that of two slip-ring motors in parallel, the upper that of a combination of one slip-ring and one Fynn-Weichsel motor. Similarly, of the two curves of line current, the lower one shows current drawn by one Fynn-Weichsel and one slip-ring motor in parallel, while the upper curve shows current drawn by two slip-ring motors in parallel.

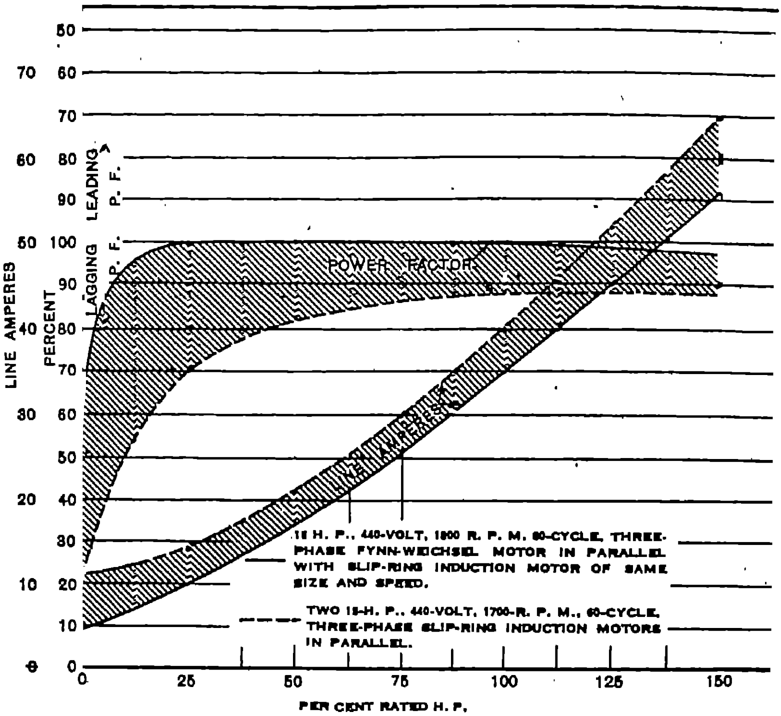


FIG. 105.—Comparison of power-factor and line current when using two slip-ring induction motors and when using one slip-ring induction motor with one Fynn-Weichsel motor.

The specific disadvantages of low power factor may be divided into three classes, as effecting service, operating cost, and fixed charges. These disadvantages are counteracted by the use of motors of this type.

The advantages may be summed up as follows :—

(1) The power-factor correction is at the most usual source of low power factor.

(2) It eliminates heavy currents drawn by synchronous motors when started or when thrown out of step, and obviates the necessity for special attendants for operation and adjustment.

(3) It eliminates the necessity for corrective means at transmission and distribution centres in so far as they may be required for industrial motor loads.

(4) It releases a frozen investment of approximately 30 per cent. for commercial sale to new customers.

(5) It reduces actual energy wasted upon the customers' premises by from 3 to 5 per cent.

(6) It makes possible a 30 per cent. reduction in cost of future plant extensions after present equipment is fully loaded.

The A.S.E.A. Motors.—Fig. 106 shows the connections of a compensated three-phase motor. The stator is of normal design, with the exception that it is provided with a small three-phase auxiliary winding having a few turns per phase. The rotor is provided with slots which are deeper than usual. The main winding lies at the bottom of the slots, and is executed exactly like the rotor winding of an ordinary three-phase motor. This carries the greater part of the working current, and it can be shortly designated as the active winding.

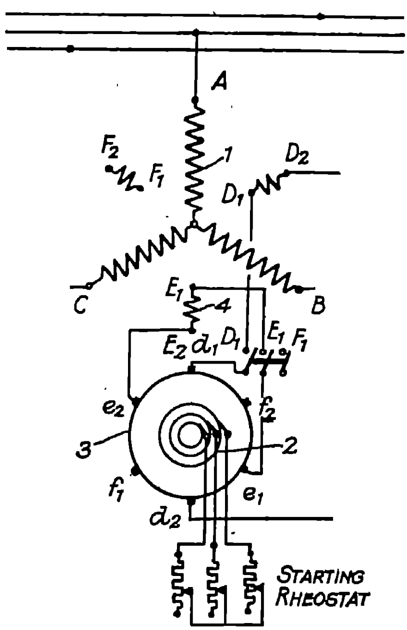


FIG. 106.—Diagram of induction motor.

Above the active winding is placed a winding which carries the magnetising current and which on this account will be referred to as the magnetising winding. This consists of a normal closed direct-

current winding with a commutator and a six-phase set of brushes. The different windings are shown in Fig. 106. The main winding on the stator constitutes the primary winding (1), which receives the current from the supply. The auxiliary winding (4) is taken to the brushes through a small change-over switch, by means of which it can be connected in series with the field winding (3).

The rotor active winding (2) is taken to the three slip-rings.

When starting the motor, the active winding (2) is connected through the slip-rings to a starting resistance of the usual type, while the change-over switch breaks the connection between the auxiliary winding (4) and the magnetising winding (3). The motor thus starts exactly like an ordinary three-phase motor with slip-ring rotor. There is, of course, one difference to be noted. In each turn of the magnetising winding the same voltage is induced as that occurring in one turn of the active winding, which lies in the same slot. Between two adjacent commutator segments there exists accordingly a voltage which is proportional to the slip, and which becomes proportionately greater with an increase in the number of turns or with an increase in the flux per pole, i.e. the greater the size of machine. This voltage is short-circuited by the brushes, which always cover more than one commutator segment.

Accordingly, if undue sparking is to be prevented, the voltage between segments must not exceed 5 or 6 volts. This limit is reached with an output of approximately 40 h.p. with 4-pole, 50-cycle machines, with about 30 h.p. for 6-pole machines and with about 20 h.p. for 8-pole machines. If it is desired to construct larger motors on the same principle for starting on full voltage, the brushes must be lifted during the start. If this arrangement is used the change-over switch can naturally be omitted.

As soon as the motor has reached normal speed, the slip-rings are short-circuited, and the slip-ring brushes lifted. At the same time, and by means of the same handle, the brushes *d*, *e*, and *f* are connected to the stator auxiliary winding, or, if the commutator brushes are provided with a brush-lifting device, these brushes are lowered on to the commutator.

As soon as this change-over has been effected the magnetising

current commences to flow in the magnetising winding, the supply is relieved from the magnetising power, and the motor is compensated.

In compensated, as in uncompensated three-phase motors, the main field which traverses the stator and the rotor is a rotating field, and the speed of the rotor during working is very close to the synchronous speed of this rotating field. The main field and the armature reaction, therefore, do not give rise to any considerable E.M.F. in the turns which are short-circuited by the brushes. The machine commutates under equally favourable conditions to those which pertain in a direct current machine having commutating poles so excited that the field due to armature reaction just disappears in the neutral commutating zone without any opposing commutating field being produced. Such direct-current machines have good commutating characteristics up to considerable outputs, and this applies also to the present form of compensated three-phase motors.

PART IV.—RECENT DEVELOPMENTS IN POWER FACTOR CORRECTION AND SPEED REGULATION OF INDUCTION MOTORS.

Although the applications of cascaded induction motor commutator groups will be described in a later chapter, with special reference to Scherbius' regulation, the following developments of recent date fall more naturally under the heading of the present chapter. The methods about to be described were communicated to the author by Brown, Boveri & Company, Ltd., who have long specialised in the design of cascaded sets of the Scherbius type. The theory of the previous methods was rather complicated, because the resultant impedance of the excitation circuit of the Scherbius machine changes very rapidly with slip frequencies, i.e. with the speed of the main motor. When the slip frequency is zero, it is equal to the ohmic resistance, but when the slip frequency increases it is almost entirely determined by the inductance, which is proportional to the slip. With the new methods, which are

really extensions of one of the first-known forms of cascade connections, the difficulty is avoided by inserting, in the exciter circuit of the Scherbius machine, a resistance which is appreciably greater than the inductance of the circuit at the maximum slip frequency. The inductance, therefore, can be neglected over the entire range without introducing any appreciable errors. In this way the exciter current is always in phase with the pressure applied, and its magnitude is obtained by dividing the pressure by the constant resistance of the excitation circuit. The losses in the additional resistance are generally small; however, should they become excessive with the usual arrangement, they can be reduced by special connections.

I. Phase Advancer for Increased Slip.—These phase advancers are employed with induction motors which operate with increased slip, in order to utilise flywheel masses (see Chapter VIII.), and ensure full compensation of the main motor at no-load, and also on load, besides effecting a partial recuperation of the slip energy. Furthermore, over-compensation can often be attained.

The phase advancer for increased slip is worthy of special attention, since all other systems of power-factor correction, with which a rotary machine is connected in the rotor circuit of the main motor, exhibit serious disadvantages if the resistance of the rotor circuit is increased in order to produce increased slip, as has been hitherto customary. All kinds of synchronous motors are inherently unsuitable in such cases. The shortcomings of the other methods used are due to the following causes.

In Fig. 106A, OA is the stator pressure, and OB the rotor pressure of an induction motor with a given slip; OC is the rotor current of the motor at full load, and with the power factor advanced to unity; hence all of the magnetisation current of the motor is taken over by the rotor. OC_1 is the watt component of the rotor current, and $C_1C = OE$, the wattless component, which corresponds to the magnetisation current of the motor. When the load decreases the watt component OC_1 falls off proportionately. The changes in the wattless current differ with the various methods of power-factor correction employed. For example, the wattless current can also vary in

proportion to the load so that with a falling load the end of the rotor current vector OC travels along a straight line from C towards O. It can, however, with an output falling from full load change slower than the load, and only falls rapidly with very small loads, so that the extremity of the rotor current vector describes the curve CDO. In both cases the degree of correction of the main motor decreases with the load, but in the second case this decrease takes place much slower than in the first.

The first example corresponds to an unsaturated phase advancer without stator, whereas the second is for the highly saturated phase advancer of the Brown-Boveri type. If the wattless current remains constant, independent of the load, the end of the rotor current vector, with falling load, travels from C to E on the straight line CE; hence complete power factor correction is obtained at all loads and also for no-load. This applies also to the frequency changer made by Brown, Boveri & Co. The greater the power-factor correction required with partial loads the greater are the current and heat losses in the rotor circuit.

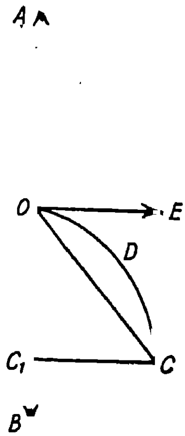


FIG. 106A.—Stator and rotor diagram of induction motor.

The various power-factor correcting systems differ also with regard to the watt output of the machine which is connected in the rotor circuit of the main motor. Certain machines, such as the Brown-Boveri phase advancer, operate with a phase displacement of 90° between the current and the pressure, their watt output is zero, and they are referred to as wattless phase advancers.

Frequency changers and other systems operate as generators and make good the copper losses due to the magnetising current of the rotor circuit. As long as the rotor of an induction motor receives no power from external sources, the slip is equal to the total copper losses in the rotor circuit divided by the output of the motor. The copper losses for a given output increase, however, with the degree of power factor correction

commutator machine to the induction machine h (Brown-Boveri-Scherbius system) the speed is kept constant. The resistance and choke coil are so dimensioned that for each load of the main motor the voltage drop in the resistance and choke coil are essentially greater than the pressure applied to the terminals of the inductance excitation winding. The principle mentioned in the introduction is also applied to the resistance excitation circuit. For a given slip-ring pressure the value of the current in the resistance and in the choke coil would scarcely change if the terminals of the excitation coils d_1, d_2, d_3, and e_1, e_2, and e_3 were short-circuited. This implies that with correct connections the current in the two windings is almost independent of the behaviour of the commutator machine, and only affected by the resistance and inductance of the choke coil. As the slip-ring pressure which feeds the two excitation circuits is proportional to the slip, the current in the resistance excitation is also approximately proportional to the slip. The current of the inductance circuit is practically constant, because the inductive resistance of the coil is proportional to the slip.

The resultant excitation field of the commutator machine is given by the sum of these two excitation currents, hence the armature pressure of the Scherbius machine is composed of a part proportional to the slip-ring pressure and also a constant component.

The resistance circuit is so dimensioned that the component of the armature pressure proportional to the slip-ring pressure is smaller than the latter and opposed to it. The resulting pressure is consequently only a fraction of the slip-ring pressure. The rotor current and torque of the motor for a given slip-ring pressure, and therefore for a given slip, are smaller than without the commutator machine; a definite torque is consequently only obtained with increased slip. The additional slip thus obtained is further augmented by means of a compound excitation winding i, traversed by the armature current of the commutator machine, which induces a further pressure in this machine proportional to the rotor current but opposed to it. The pressure necessitated by means of the inductance excitaton winding lags 90° behind the pressure of the resistance winding, and effects phase advancing.

In Fig. 109, OA is the induced pressure in the stat main motor, OB the induced pressure in the rotor corre to a definite slip, OC is the rotor current with phase adva OD is the corresponding total pressure drop in the rotor circuit, and OD_1 the drop in the rotor of the mai alone. D_1B is the pressure across the slip rings, whil the resulting induced pressure in the advancer. This consists of the pressure BE in the opposite direction current, and due to the compounding winding EF corresponds to the resistance winding and is almost opposed to the slip-ring pressure, and FD in quadrature with EF, and produced by the inductive excitation winding. The pressure components of the rotor circuit acting in the direction of the slip pressure are approximately proportional to the load, thus also the slip pressure OB and the slip must be proportional to the load. The pressure FD, perpendicular to slip pressure, is approximately constant, and the same applies to the magnetisation current OC, taken over by the rotor which is independent of the slip. From Fig. 109 it is apparent that the greater the number of the compound turns the greater the pressure BE, and consequently also the pressure FD, and therewith the choke coil, while the pressure EF, caused by the excitation resistance circuit in the armature, becomes smaller. The object of the compound winding is primarily to reduce the losses in the resistance circuit and moreover, to damp out the effects of any disturbances liable to occur.

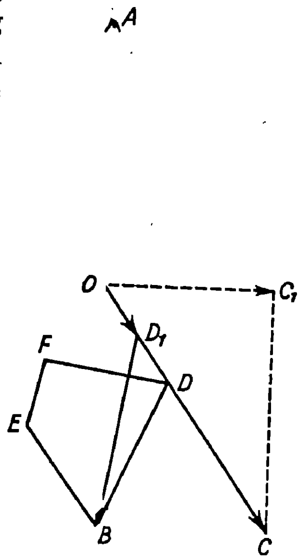


FIG. 109.—Pressure diagram for the rotor circuit of an induction motor with phase advancer for increased slip.

As FD, the pressure component of the commutator machine, is nearly in phase with the magnetising current, it covers the heat losses in the rotor circuit, complete phase correction with small loads is attainable without interfering with the

proportion between the load and slip. The unfavourable effect on the efficiency experienced with certain of the previous methods is avoided.

Moreover, the increased slip is produced by means of the phase advancer, and not by switching in a resistance. A considerable reduction of the total loss results through utilisation of the slip energy when this kind of installation is compared with an uncompensated motor. The phase advancer for increased slip runs as a generator for as far as it is called upon to cover the magnetisation losses in the rotor circuit, whereas it runs as a motor when taking up the slip energy of the main motor. The magnetisation losses are approximately constant and independent of the slip; the slip energy is proportional to the square of the slip if the slip is proportional to the load. The magnetisation losses preponderate with small loads. The advancer then runs as a generator, and its driving motor takes power from the system, which can exceed the power saved by phase advancing in the stator of the main motor. In this case, small additional losses are involved owing to the phase advancing. These, however, are always notably smaller, even with the main motor on no-load, than those of a synchronous motor running light, by means of which the same amount of wattless power is returned to the system. Often the basic load of the main motor provided by the friction losses is so large that even at basic loads the slip energy greatly exceeds the magnetisation losses, the commutator machine runs, therefore, as a motor and returns power to the system, which must be added to the power saved in the stator.

In this case a saving of energy is effected concurrently with phase advancing, even with the main motor practically on no-load. Since the slip energy recuperated increases proportionally to the square of the slip, the size of the auxiliary machine for taking up the slip energy, coupled with the commutator machine, is principally determined by the working conditions on overload. With an additional slip of the main motor of about 6·0 to 10 per cent., the overall efficiency of the motor is only 2·0-3·5 per cent. smaller than when running without increased slip. If an equal slip were produced by inserting resistances, the efficiency would fall off by 6·0 to 10

per cent. The larger the slip desired, the greater the energy saved. The slip is proportional to the load, up to about 30-60 per cent. overload of the main motor. With higher loads this usually no longer holds owing to saturation of the commutator machine. At 100 per cent. overload, the slip amounts to about 1·7 times to twice the full-load value. Changes in the resistance excitation circuit produce a different degree of slip for a given load, thus the amount of the additional slip can be regulated. The exceptionally good results on the power factor obtained are shown in Fig. 110. The circumference *a* gives the current diagram for a 880 kw. motor without phase advancing; A is the full-load working point. The power factor at full load is very poor, owing to the low speed of the motor. The curve *b* shows the current diagram, a phase advancer for an additional slip of 8 per cent. having been fitted. At full load, A, the motor still runs with a slightly leading power factor. On overload the lagging wattless component increases much more slowly than for the uncompensated motor. This is brought about by an extremely favourable secondary action of the resistance excitation circuit. The inductive resistance depending on this slip is, however, small when compared with the ohmic resistance, but is not entirely without effect with a large degree of slip. It causes a phase displacement of the exciter current, and a corresponding lagging component of the rotor pressure EF (Fig. 109). Owing to this lagging, a pressure component is set up in the direction of the voltage of the choke coil. This increases with the slip and improves the power factor, especially on overload. An exceptionally large overload capacity of the motor, for a short time, accompanies the improved power factor, and it is considerably larger than that available with uncompensated motors. To use this in practice, the driving

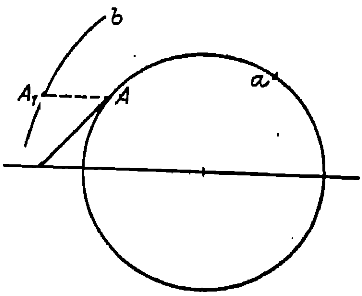


FIG. 110.—Stator current of an induction motor.
(*a*) without phase advancer;
(*b*) with phase advancer for increased slip.

machine of the advancer must be amply proportioned. It is usual to dimension the installation for 100 per cent. momentary overloads.

With an uncompensated induction motor, the no-load speed is synchronous speed, the slip frequency and slip pressure being practically zero. If this speed was maintained, even after the phase advancer had been connected, this machine would become ineffective on no-load, as there would be no pressure in the rotor circuit, moreover, the choke coil *g* (Fig. 108) would lose its inductive character with a zero frequency and only act as a small resistance. The choke coil excitation circuit is arranged, however, in such a manner that the main motor, even when entirely without load, still has a small slip (0·5-1·0 per cent.), i.e. sufficient for the inductance of the choke coil to have effect. With no-load, therefore, complete, or nearly complete, power-factor correction is attained.

If the main motor runs above synchronous speed, owing to its being driven from an external source, although it then runs as a generator, the change from motor to generator does not affect the phase advancer, which continues to effect the compensation, so that a switch is not necessary when passing through synchronism.

At the instant of passing through synchronous speed, the phase advancing diminishes, but this phenomenon is of little importance, and can only be detected by careful observation of the instruments. The phase advancer, therefore, retains its favourable properties under all possible working conditions. It offers an exceptionally good solution, with simple connections, for problems relating to the phase advancing of induction motors which run with increased slip. Whereas phase advancing is otherwise almost always accompanied by increased losses, here it effects a considerable reduction of the total losses, hence the initial cost of the phase advancer for additional slip is repaid in a very short time.

With the methods dealt with hitherto, the no-load speed of the main motor is a little below synchronous speed, but by slightly changing the connections, however, this speed can be raised slightly above synchronism. Fig. 111 shows the magnitude of the pressure occurring in the rotor circuit, as far as it

influences the speed. The components affecting the phase advancing are neglected; Fig. 112 shows the connections required to obtain this diagram. With reference to Fig. 111, AA_1 is the slip-ring pressure of the main motor with the sub-synchronous slip OA. If the slip varies, the point A_1 travels along the straight line A_1A_2. The portion OA_2 is that for the super-synchronous running. The straight line B_1B_2 shows the pressure required in the resistance winding of the advancer; this pressure is proportional to the slip-ring pressure, but opposes it. C_1C_2 is the pressure in the rotor circuit resulting from the

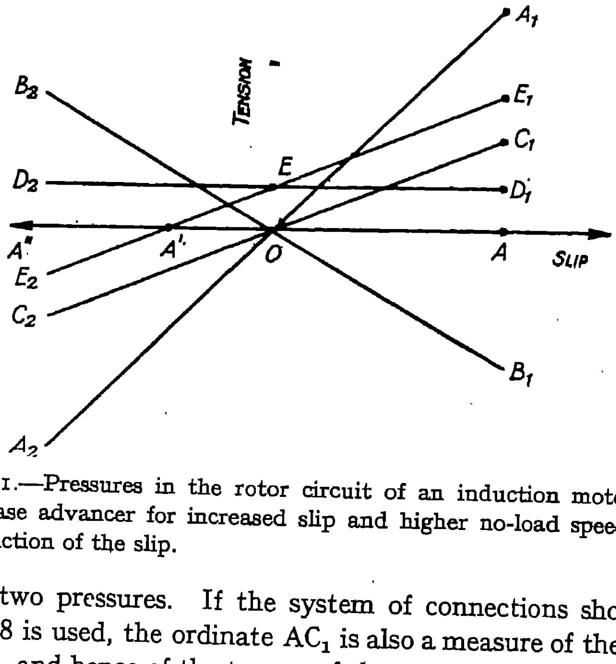


FIG. 111.—Pressures in the rotor circuit of an induction motor with phase advancer for increased slip and higher no-load speed, as a function of the slip.

above two pressures. If the system of connections shown in Fig. 108 is used, the ordinate AC_1 is also a measure of the rotor current, and hence of the torque of the motor with the slip OA. If an additional and constant excitation current independent of the slip is introduced into the excitation circuit of the advancer, it causes another pressure component in the rotor of the advancer, and can be represented by AD_1. When the slip varies the point D_1 moves along the straight line D_1D_2, parallel to the abscissæ axis. The resultant pressure in the rotor circuit is now given by the vertical distance from the abscissæ axis AA'' to the straight line E_1E_2 (where $C_1E_1 = AD_1$). The

power with the slip OA is no longer represented by AC_1, but by AE_1, hence this also has increased. At synchronism the power is no longer zero, but is represented by OE. Zero is first obtained with the super-synchronous slip OA′, where the line E_1E_2 cuts the abscissæ axis. With a greater super-synchronous slip, and at a higher speed, the main motor runs as a generator. The variation of the speed from this no-load value is again proportional to the load; the main motor runs under similar conditions as obtained by the former connections, but with a higher no-load speed.

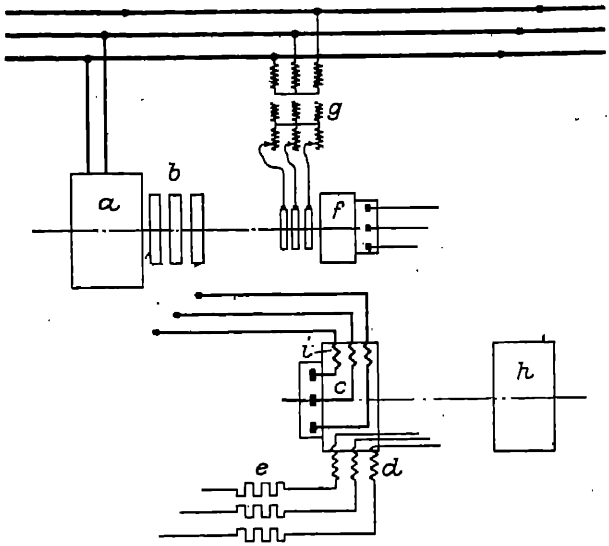


FIG. 112.—Connections of a phase advancer for increased slip and for higher no-load speed.

In order that a constant supplementary current may flow in the resistance excitation circuit of the advancer, a constant supplementary pressure must be applied to its circuit, which is effected by means of the frequency changer (*f* in Fig. 112) driven from the main motor. The remaining connections are similar to those shown in Fig. 108. In both illustrations ***a*** to ***d***, ***h***, and ***i*** designate similar parts; ***e*** is the additional resistance in the excitation circuit, and *g* an auxiliary transformer supplying the frequency changer. Compared with Fig. 108, the inductive excitation circuit which is used for supplying a constant excitation

has been dispensed with. In this case, this function is fulfilled by the frequency changer, which, apart from the current just mentioned, produces a constant pressure, having a phase displacement of 90° for the excitation circuit, whose effect is to correct the power factor independently of the load. The magnitude of the pressure AD_1 (Fig. 111) can be adjusted by changing the secondary pressure of the transformer *g*, and by varying the resistance *e* (Fig. 112); the inclination of the straight line E_1E_2 can be adjusted at will by simply altering the resistance *e*. The no-load speed and additional slip are also able to be adjusted. These connections can also serve to give the main motor a compound characteristic; they are applicable only if slight regulation of the no-load speed, but a large speed drop, is required, thus affording another kind of speed regulation obtainable by the Brown-Boveri-Scherbius system.

Provided that only a single no-load speed above synchronism is required, it is best chosen so that the total speed range is approximately distributed about the synchronous speed. The maximum slip of the main motor, and its corresponding slip power, are thus only about half as large for an equal total speed range as if the motor runs synchronously at no-load. The size of the commutator machine, its driving motor, the resistance in the exciter circuit, and the losses are consequently also appreciably reduced. A disadvantage of this system, when compared to that shown in Fig. 108, is incurred through use of the frequency changer, which must be driven by the main motor. It is, therefore, necessary to examine each individual case in order to decide whether it is advisable to use this somewhat complicated system; it is primarily applicable to instances requiring large speed ranges. Generally it is preferable to run the motor only below synchronism. Phase advancers for increased slip have already been manufactured in large numbers, and have proved to be satisfactory in service.

II. The Commutator Cascade for Constant Output.—This method can be developed from the connections shown in Fig. 112 on page 164, and can be considered as a phase advancer for infinitely large additional slip. In the previous systems, the output of the motor changed with the speed much less than if the main motor were to work with a short-circuited rotor.

With the commutator cascade for constant output, the output should not be influenced at all by the speed, and should therefore remain constant. Only with an infinitely great slip does a change in the output occur if the secondary influences are neglected. This method of working is desirable if two distribution systems, fluctuating in frequency, are coupled by motor-generators, and also when Ilgner converters are used.

Whereas formerly constant output with changing slip could only be obtained by means of regulating devices (either operated by hand or automatically), the following methods ensure constant output of the main motor without any regulating devices being necessary.

Slip Regulation of Ilgner Converter Sets.—The main motor of Ilgner sets must take constant power from the distribution system, independently of the speed. The difference between the constant output and the output momentarily required by the plant is supplied or taken up by the changes in speed of the flywheel coupled to the main motor. The output of the main motor will be constant, in spite of the speed variation, if the motor is fitted with commutator cascade for constant output. The automatic control of the induction motor usually provided with Ilgner converter sets is, therefore, no longer necessary.

The principle of the connections is similar to that described, with the exception that the slip frequency employed is much greater than with a frequency changer, the usual value being about 10 cycles per second. With this frequency the inductive resistance of the exciter circuit is already considerable, and the ohmic resistance connected in series with it would involve losses that cannot be allowed in practice. This resistance is therefore replaced by a commutator exciter machine. This is a machine driven at a constant speed, the field being excited by the armature current so that it is therefore a series machine. A pressure proportional to the rotor current is induced in the armature as long as the saturation can be neglected. As the pressure is in the opposite direction to the current the exciter machine operates as an ohmic resistance, but transforms the energy which would otherwise be wasted as heat into mechanical energy, which can be returned to the distribution mains through an induction machine. Another notable difference with respect

to the method of operation of the frequency changer is that with an Ilgner set it is not allowable to continue to drive the flywheel during lengthy unloaded intervals, but the output of the main motor must be reduced to zero when synchronous speed is attained, with the result that the flywheel cannot be driven above this speed. If the plant connected to the converter set now returns energy a further increase of speed is unavoidable. Under such conditions the main motor must run as a generator and absorb this energy in conjunction with the flywheel. Consequently the main motor must only operate in the sub-synchronous range according to the commutator cascade principle for constant output. The main motor and commutator machine are connected as shown in Fig. 112. The frequency changer *f*, however, is omitted, as it would have the same action at synchronous speed as at asynchronous speeds.

Its duty is carried out by an inductive circuit connected to the slip-rings of the main motor; the connections for the inductive circuit are the same as for the phase advancer with increased slip. The current in the choke coil remains constant down to very small slip frequencies, i.e. as long as the inductive resistance of the choke coil is larger than the ohmic resistance.

When the slip frequency is zero, however, the current is also zero as the slip pressure supplying the current is also zero, the ohmic resistance of the circuit, however, remaining constant. The connections are given in Fig. 113, which shows only the main motor *a* of the Ilgner converter set. The commutator machine *c* directly coupled to the main motor is connected to the slip-rings of the control motor. The exciter machine *e* is coupled with the induction machine *f*, and its armature pressure, in conjunction with the slip-ring pressure of the main motor, is impressed upon the field winding *d* of the commutator machine. Besides the induction winding *g*, the excitation machine has a compound winding *h*, through which the rotor current flows. The current flowing in the compound winding *h* induces a voltage in the armature of the exciter machine proportional to this current, but in the opposite direction. The commutator machine and the exciter are designed so that this pressure is much larger than the induced voltage of the field winding *d*. The latter voltage may be neglected without the introduction

of an appreciable error. If the influence of the inductive excitation winding is now also neglected, the pressure induced in the armature of the exciter by the compound winding must be approximately opposite to the slip-ring pressure of the main motor, and consequently the current in the excitation circuit *d* of the commutator machine must be proportional to the slip-ring pressure. The exciter machine influences the resistance excitation circuit in the same way as the resistance in the systems previously used. The number of turns of the compound winding is so chosen that the pressure induced by the exciting current in the rotor of the commutator machine *c* is also equal

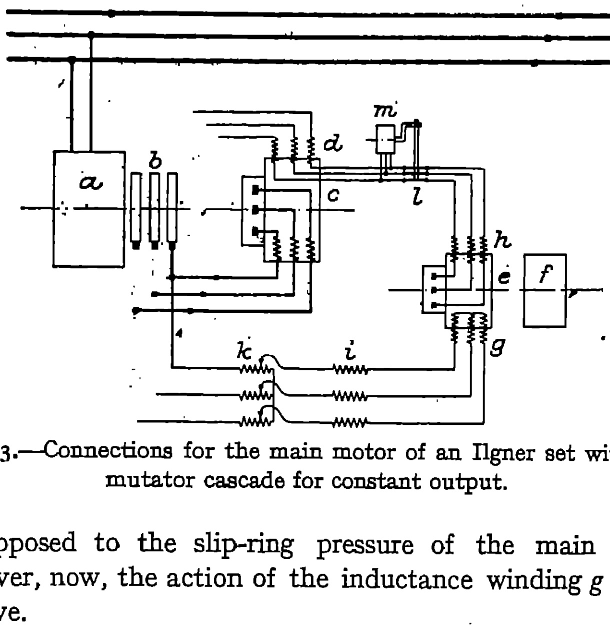


FIG. 113.—Connections for the main motor of an Ilgner set with commutator cascade for constant output.

but opposed to the slip-ring pressure of the main motor. Moreover, now, the action of the inductance winding *g* is also effective.

Its current induces a constant pressure in the armature of the exciter, which is independent of the slip as long as the main motor runs with some slip. This produces a constant additional excitation current of the commutator machine *c*, and hence a constant armature pressure of this machine. As the other pressures occurring in the rotor circuit of the main motor mutually balance each other, the constant pressure alone remains, and the connection acts similarly to that shown in Fig. 112. If the slip of the main motor goes back to zero, the

current in the induction winding, together with the additional pressure of the commutator machine, disappears. The resultant pressure in the rotor circuit and its output become zero. Power-factor correction is again obtained by a pressure component induced by the induction current and displaced by 90°. By special measures it can persist also with no-load if the influence of the inductive circuit disappears. By means of a transformer *k* with a variable pressure ratio, it is possible to adjust to any desired value the potential impressed on the inductive excitation circuit at a given slip, and hence also the additional pressure in the armature of the commutator machine *c*, and the output of the main motor.

If with these connections the main motor is made to run above synchronous speeds, owing to its being driven externally, it would again work as a motor and continue to accelerate. To avoid this, the excitation circuit of the commutator machine is opened by the switch 1 as soon as synchronous speed is passed, with the result that it is no longer effective, and the main motor brakes as a normal induction generator.

By means of the commutator cascades for constant output, the general advantages of the commutator cascade are realised, i.e. improvement of efficiency and power factor of the main motor in such cases where constant output of the motor is demanded without the necessity of automatic regulation.

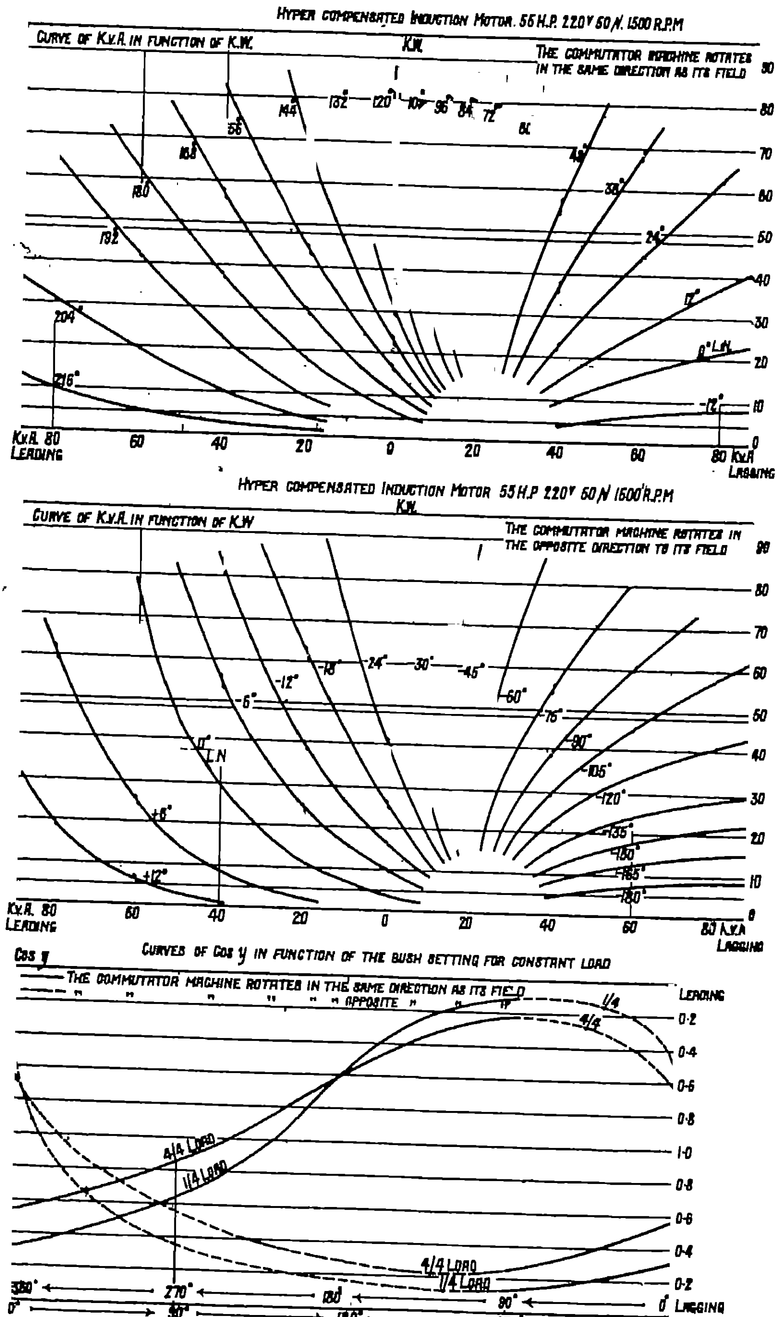
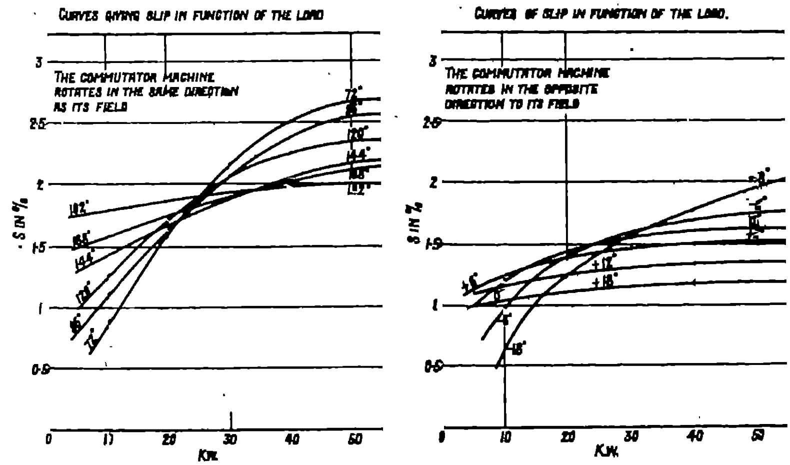


CHART I.—Test curves for 55 h.p. motor (Jeumont).



Slip-load curves for 55 h.p. motor (Jeumont).

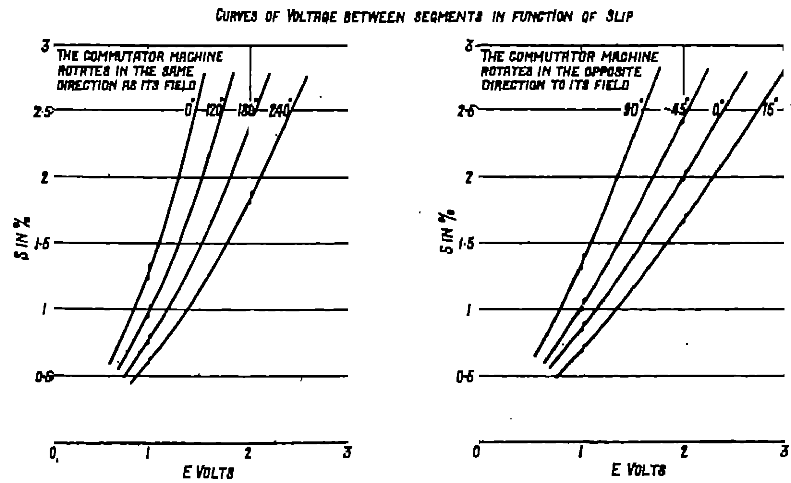


CHART 2.—Test curves for 55 h.p. motor (Jeumont).

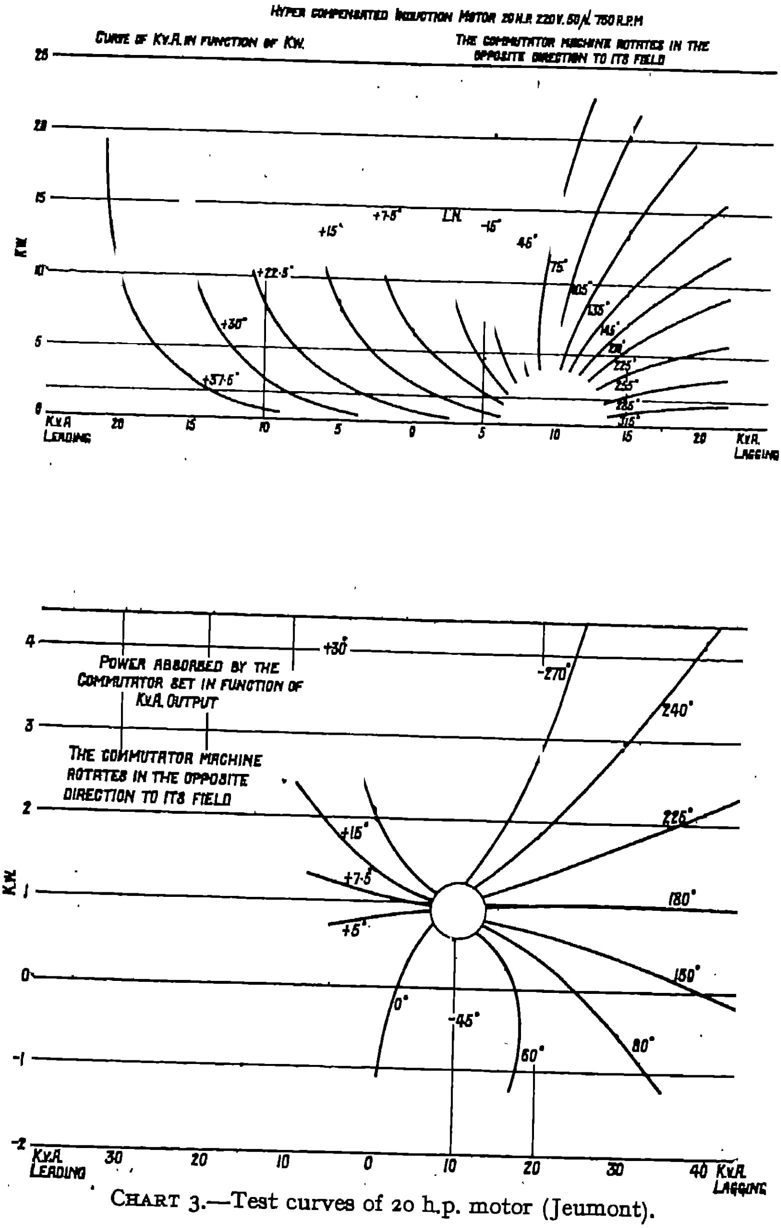
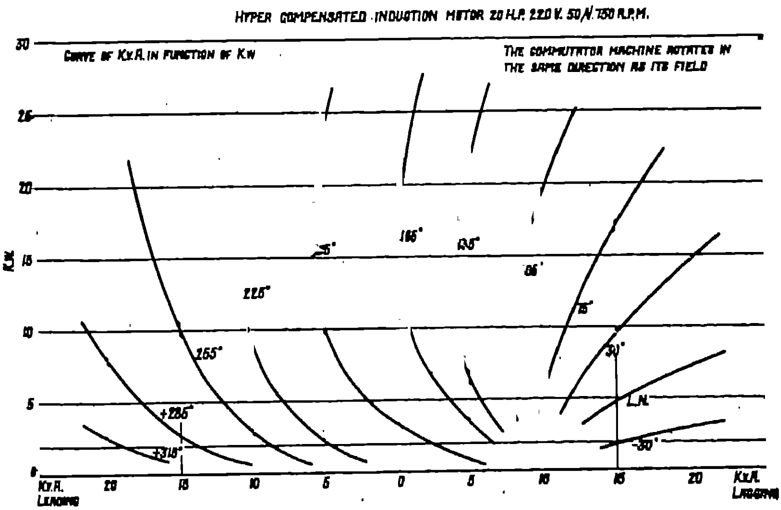


CHART 3.—Test curves of 20 h.p. motor (Jeumont).



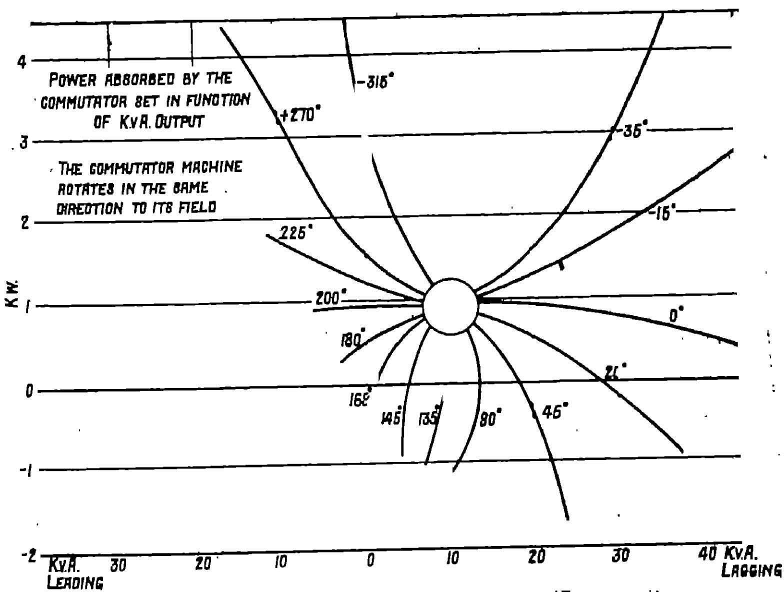
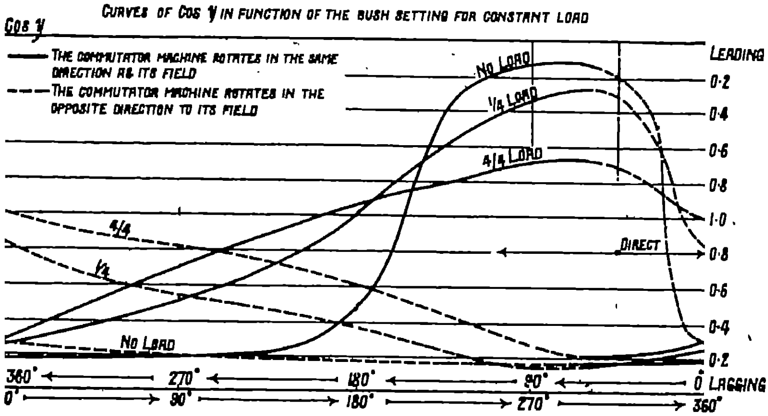


CHART 4.—Test curves of 20 h.p. motor (Jeumont).



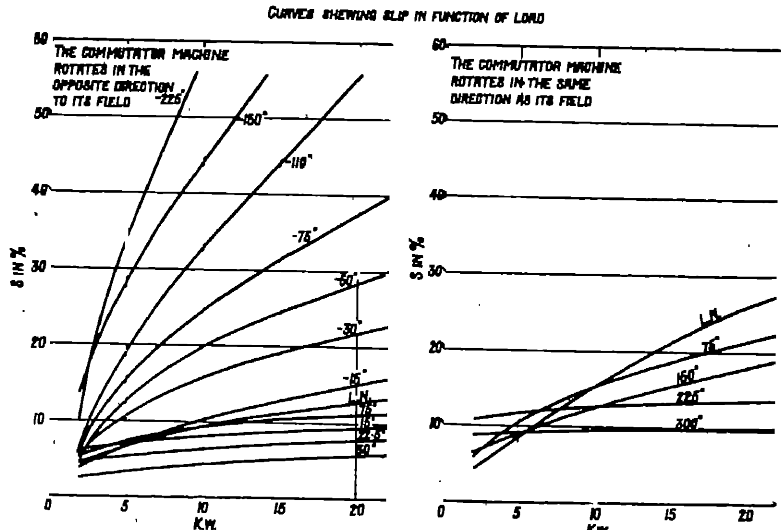


CHART 5.—Test curves (Jeumont), showing power factor and slip curves.

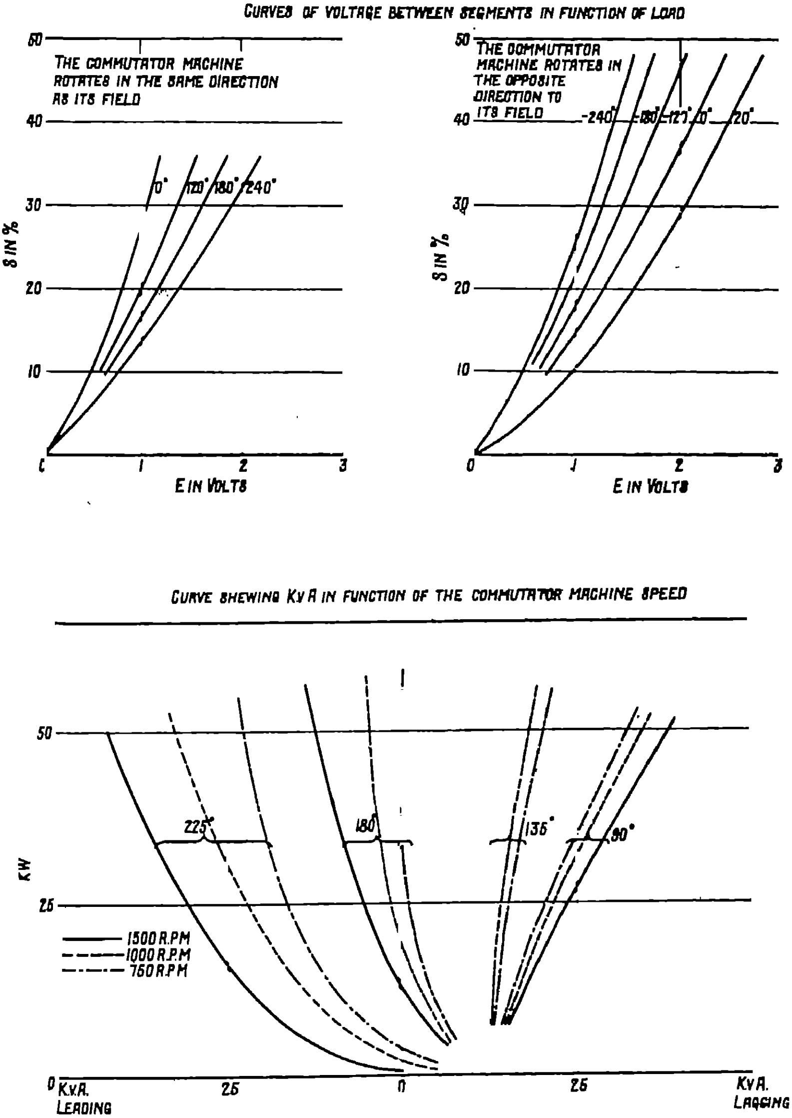


CHART 6.—Test curves (Jeumont), showing voltage between segments and kVA in junction of speed.

PART II.

PRACTICAL APPLICATIONS.

CHAPTER VI.

CRANES AND HOISTING APPLIANCES.

THE continual increase in transport is reflected in the correspondingly heavy demands upon loading and unloading equipment, particularly hoisting appliances, and the requirements as to lifting capacity and speed which have to be satisfied in designing such equipment become more and more exacting every day. Let us take, for instance, the case of a wharf crane intended for both grab work and also for handling slung loads of widely varying weights. In such a case an extensive range of speed is absolutely essential.

Crane Motors.—The first application of the commutator motor that comes under the notice of engineers is the drive of cranes, and similar variable speed-handling plants.

This type of motor had been previously successfully employed to a considerable extent for traction and winding purposes, the requirements of which are in many respects identical with those of crane operation. The single-phase commutator motor (with Déri connections) is suitable for all drives requiring high starting torque and speed regulation, and a very large number have been constructed both in this country and abroad, in different forms, for work of this character. From a constructional point of view, this motor is particularly robust and solid, while the electrical design is exceedingly simple. The stator winding is an ordinary single-phase winding of the simplest character, the ends being brought out to two terminals on the stator housing for connection to the supply circuit

through a two-pole switch and fuses. The armature is similar to that of an ordinary direct-current motor, except that the commutator is provided with two sets of brushes, one of which is fixed, and one movable, which are inter-connected among themselves. Neither the rotor nor brush system are in any way connected with the supply circuit. The whole control of the motor (starting, speed regulation, and reversal) is effected by the displacement of the movable set of brushes, no starting or regulating resistances whatsoever being employed. When the stator switch is closed, the motor takes only the magnetising current from the line, this current being about one-third of the full-load current, and it will remain at a standstill until the movable brushes are displaced from their neutral position. The torque developed by the motor, and the starting current, will then gradually increase up to a maximum, and in comparison with the high starting torque exerted by the motor, the starting current is very low. The direction in which the rotor turns is opposite to that in which the brushes are displaced. For each position of the brushes the motor has practically a series characteristic, the speed varying inversely with the load. Consequently, when used for crane work, the driver, by a movement of the brushes, can adjust the torque and speed to suit the load in such a manner that the current taken from the supply is always a minimum. He can also vary the speed at his discretion when lifting, lowering, or traversing.

Another important feature of this form of control is that the different motors of the crane are capable of exceedingly fine adjustment, so that a load can be taken up and placed in any required position with great accuracy. This is a special advantage for foundry and erecting shop cranes. By bringing the brushes back beyond the neutral position, regenerative braking of the hoisting motor can be obtained when lowering a load, the braking action being continuous and without shock. The different motors are erected on the crane in the usual way, the stator switch for each being fitted close by the motor and operated by a link from the brush control gear. By means of a suitable limit switch, the main switch for the lifting motor can be opened when the full extent of the lift has been reached. In a similar manner the cross traverse movement can be limited.

The brakes when required can be operated either by means of a single-phase brake magnet or by a special brake motor. The electrical installation is of the simplest order, only two leads and two collecting wires being required throughout. The mechanical brush control can be effected either from the floor

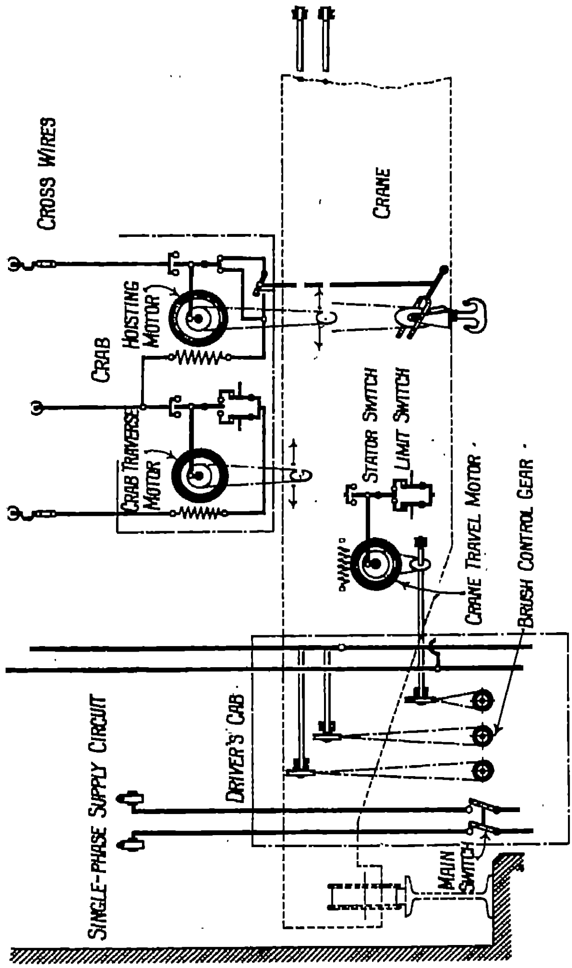


FIG. 114.—Typical connections for crane control.

or from a driver's cage carried on the crane. For the longitudinal travel motors, either a chain or simple lever transmission is employed, while in the case of the crab traverse and hoisting motors the brushes are operated from a sleeve, carried by brackets attached to the crab frame, which slides along a square

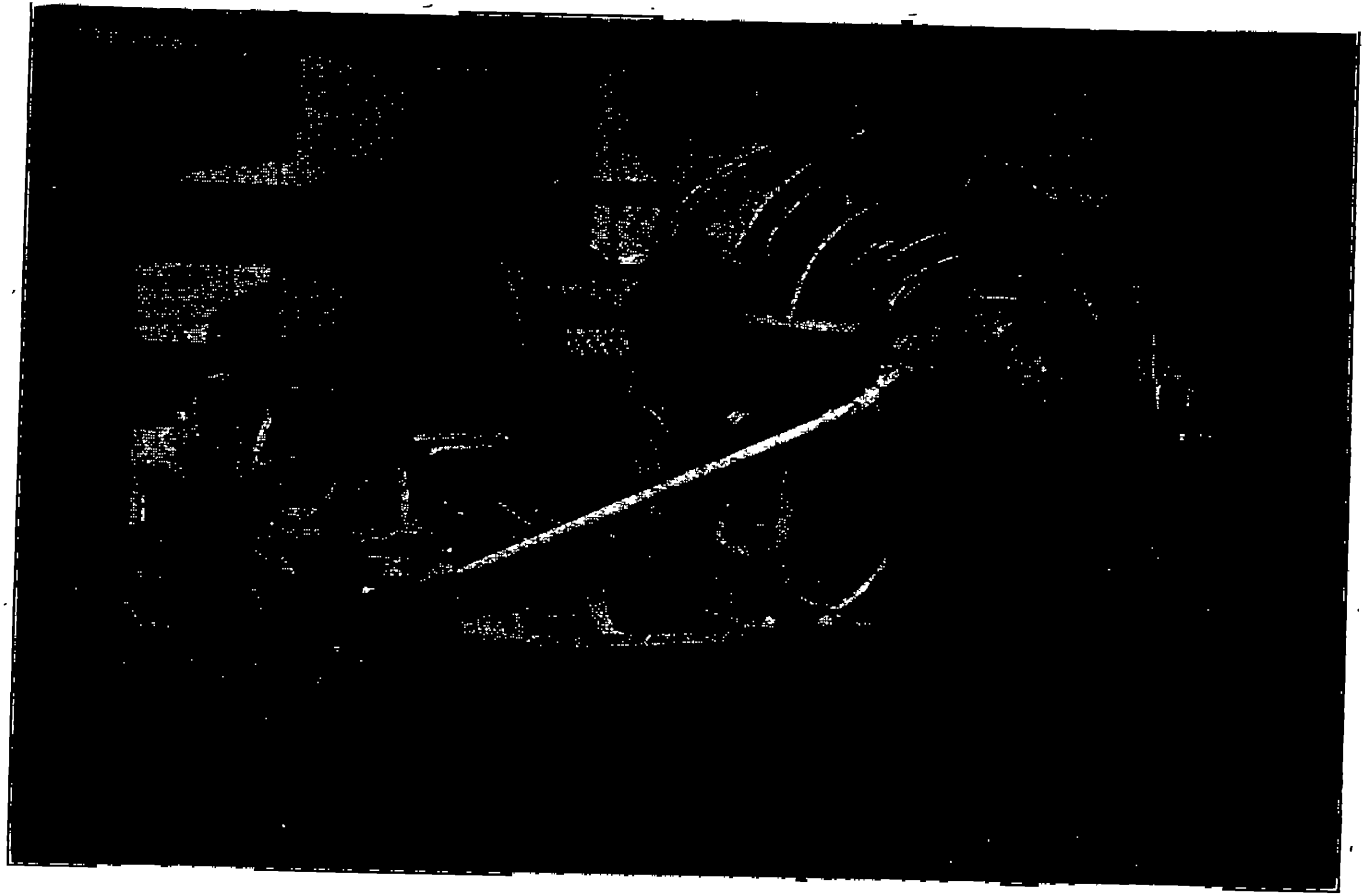


FIG. 115.—Brown-Boveri three-phase crane motors.

shaft running the whole width of the crane, and is operated from the driver's cab. In the case of long spans, this shaft is supported at intervals by swing bearings. Beyond the main switch and ammeter, the driver's cab contains nothing but the control levers or hand wheels for the different motors on the crane. In the case of slewing or gantry cranes for harbour work, the control rods for the brush rockers are arranged beneath the floor of the cab in which the motors are housed.

The operating rods for the crane and gantry travel motors are brought through the centre pin of the cab. Where mechanical brush control presents complication, however, a simple form of electrical control may be employed. A very large number of cranes equipped with single-phase commutator motors are in service and have proved thoroughly reliable and satisfactory (see Fig. 114).

As an example of recent orders for this type of equipment, it is interesting to note that the Yorkshire Electric Power Company have placed an order with the British Brown-Boveri, Limited, for a crane at their new Ferrybridge power station. Four motors will be used on the crane as follows: Hoisting: One 50 b.h.p. motor. Travelling equipment: One 20·5 b.h.p. motor. Luffing equipment: One 10 b.h.p. motor. Slewing equipment: One 10 b.h.p. motor. These motors will be provided with control rods operated from the driver's cabin. Three-phase commutator motors are also used for crane equipments, the installation being precisely similar in every respect. An example of this is shown in Fig. 115.

If, when a single-phase commutator motor is running the brushes be displaced from the zero position in the reverse direction, the motor exerts a braking torque which increases smoothly with the brush displacement, power being returned to the mains. As with all alternating-current commutator motors, however, self-excitation effects are involved which under certain circumstances may prove harmful, and must therefore be prevented. This can be effected in a simple way by introducing a resistance between the stator and the mains. For reasons of economy, and in order that the torque may not be reduced, this regenerative braking resistance is only put into circuit when the motor is working as a generator.

The switching in and switching out of this resistance does not depend upon the operator, but is effected by a contactor actuated by the master switch.

On account of its series characteristic the single-phase commutator motor tends to run away in exactly the same way as a direct-current series motor on no-load, or whenever the load is sufficient to overcome the friction of the gearing. If the pairs of brushes are mutually short-circuited, however, its characteristic becomes similar to that of an induction motor, and whatever the load the speed will assume a value in the neighbourhood of synchronism. The brushes are short-circuited by a centrifugal switch incorporated in the rotor which actuates a contactor.

A particular advantage of hoisting appliances fitted with single-phase commutator motors is that whatever the position of the brushes, the speed is limited by the closing of the centrifugal switch, so that there is no " free " position of the control lever, i.e. a position of the controls for which the motor exerts no torque at all, which can naturally be extremely dangerous. This does occur, for example, with direct-current motors when switching over from the braking position to lowering with power, as this involves disconnecting the motor from the mains while the polarity is reversed, before the machine is again excited. While this is being carried out, the motor naturally exerts no braking effect at all.

With the single-phase commutator motor when lowering, the change from braking to power, or from power to braking, is effected by moving the brushes over the neutral zone without disconnecting the stator from the mains. With the brushes either in the neutral zone or in the position for power lowering, the motor torque becomes a braking torque should the speed increase excessively.

Examination of a Typical System of Control.*—The control described is designed for use with single-phase commutator motors for loading equipment, foundry, and erection-shop cranes, and in all instances where a crane with a fine control is required.

* SNS control, Brown-Boveri.

The controller is so designed that the motion of the lever always corresponds to that of the load, i.e. both when hoisting and lowering, the speed of the load increases or decreases to an extent approximately proportional to the lever displacement (natural control). As the lever is moved in the direction for lowering, there is a gradual change from braking to power lowering, the greatest braking torque being exerted when the lever is in the neighbourhood of the zero position, while the lever positions for power lowering are at the end of its range of movement.

On account of this arrangement, combined with the characteristic of the motor, it follows that the negative torque, the value of which is greatest near the zero position, decreases as the lever is moved over in the direction for lowering and gradually changes to a positive torque.

In this way the possibility of heavy loads running away as soon as lowering is commenced, is entirely eliminated. In addition, every time the lever is returned to the zero position absolutely smooth electrical braking takes place which, as already mentioned, saves the mechanical brakes and the drive. By means of the controller the stator switch is closed, and the motor brushes shifted. When the control lever is in its zero position, the brushes are slightly displaced in the direction for hoisting.

The displacement increases as the lever is put over, the maximum brush displacement of 150° electric corresponding to its end position. The master switch for actuating the contactors can be combined with the operating stand, or it can be fitted separately and connected to the lever by suitable linkwork. Upon moving the lever over for lowering, the motor operates as a brake, the braking torque being most powerful at first, as the brushes are still displaced somewhat in the hoisting side before the stator switch is closed. As the lever is moved further in the same direction, the brushes pass gradually into the neutral zone, the braking torque being correspondingly reduced, and eventually giving place to a power torque as the lever approaches its limiting position.

The manner in which the brushes are moved is shown in Fig. 116. The range of regulation on the hoisting side is

sufficiently great to enable the speed to be regulated as desired, whether the load is large or small. The maximum displacement of the brushes for braking, i.e. the maximum braking torque and also the maximum displacement for power lowering, can be adjusted simply by varying the velocity ratio of the link-work.

Fig. 118 is a diagram of the connections used. The contactor

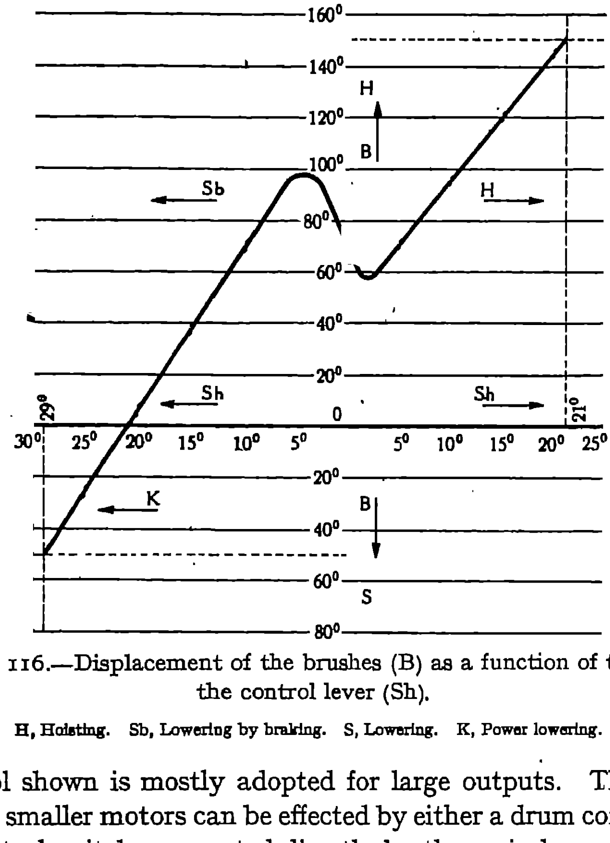


FIG. 116.—Displacement of the brushes (B) as a function of that of the control lever (Sh).

H, Hoisting. Sb, Lowering by braking. S, Lowering. K, Power lowering.

control shown is mostly adopted for large outputs. The control of smaller motors can be effected by either a drum controller or control switches operated directly by the main lever.

In the case of the system illustrated (Fig. 118), if the lever is moved in the direction for hoisting, the contact segments of the master switch incorporated in the controller meet the contact fingers shown on the left-hand side, with the result that the stator contactor 5, the hoisting contactor 6, and the solenoid brake contactor 4 close, corresponding to contacts a_1, a_2, and

h_1 and h_2. The brake solenoid 13 then raises the mechanical hold-on brake coupled with the hoisting gear, and the motor 1 being connected to the mains through the contactors 5 and 6, commences to rotate. As the lever is moved further over in the direction for hoisting, the brushes are displaced more and more with a corresponding increase in the torque and speed. Under certain circumstances, with high-efficiency hoisting gear,

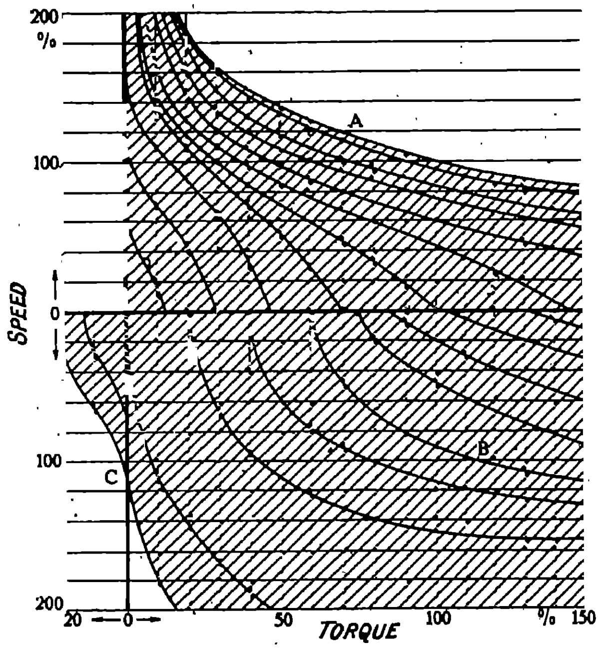


FIG. 117.—Regulation curves of single-phase commutator motor for hoisting control as a function of the torque.

A, Hoisting. B, Lowering by braking. C, Power lowering.

it would be possible for the motor to reach an excessive speed when raising the empty hook with the control lever in the extreme position. This is prevented by the centrifugal switch 12, which, at the speed for which it is adjusted, closes an auxiliary circuit, whereupon the pairs of brushes are short-circuited over the limiting resistance 11 by the contactor 7.

If the control lever is moved back towards the zero position, torque and speed are reduced and the centrifugal switch opens,

the pairs of brushes being disconnected again. To prevent over-winding, a limit switch 14 is fitted. When the load has reached the highest point allowable, this switch comes into action, breaking the circuit of the stator and solenoid brake contactors, thus bringing the load to rest. It is still possible, however, to lower the load, simply by putting over the control lever to the other side of the zero position; the contact segments of the master switch then meet the contact fingers a_3-h_4 on the right-hand side, which short-circuit the open-limit

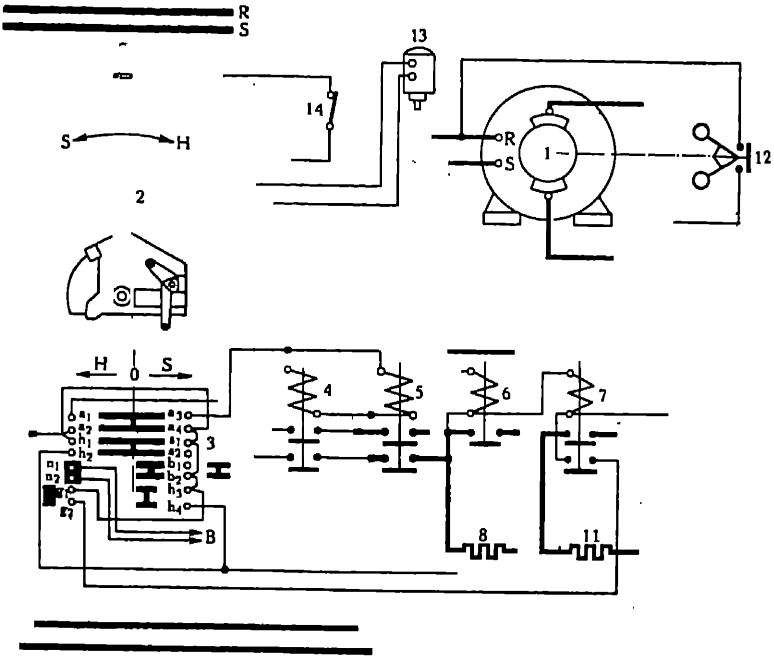


FIG. 118.—Diagram of connections of the SNS control.
B, No-volt interlocking device.

switch and actuate the stator and solenoid brake contactors as before. The resistance 8, by which self-excitation is prevented, remains in series with the stator as long as the contactor 6 is not energised. As the control lever is moved further, the brushes pass through the neutral zone into the power lowering range. At the point when this occurs, the contactor 6 is actuated through contacts h_3 and h_4, the resistance 8 being short-circuited and the motor connected directly to the mains.

Should the speed become excessive as a result of careless

operation of the controller, the centrifugal switch comes into action in the same way as already described. It is safer, however, for the brushes to be kept short-circuited all the time when lowering under power, and only to return to normal connections when the braking torque is so great as to hold the maximum load safely. This is effected by contacts g_1 and g_2.

The Simple Lowering Control.—With this system of control, braking is not effected by putting the lever over to the lowering side, as in the system described above. When the load has reached the desired speed the lever is moved back from the lowering side, through zero, to the hoisting side, i.e. counter-current is applied. The braking torque increases in proportion to the displacement of the control lever from the zero position, and the actual operation is extremely simple.

Either of two control levers can be employed. In the one, the lever is combined directly with the stator switch, and also, if desired, with a no-volt release. The control lever used in connection with a master switch operates the stator contactors of higher powered motors. The other type of control lever is provided with a small auxiliary lever, which enables it to be moved through the zero position without the combined stator switch opening so that the brake solenoids do not release the brakes. The diagram of connections for a controller with combined stator switch is shown in Fig. 119. Upon the control lever being moved over to the hoisting side, the stator of the motor is connected to the mains through the resistance 4. It is assumed that the switch 8 has been opened at the conclusion of the preceding lowering operation. The motor now begins to rotate and the switch 8 is closed, energising the contactor 9, which short-circuits the resistance 4, so that the motor is connected directly to the mains. If the lever is moved to the lowering side a similar process takes place. If it is desired to brake the lowering, or to lower heavy loads at slow speeds, the operator moves the lever through the zero position to the hoisting side.

The lever of the operating stand, as with the combined stator switch, can be moved through the zero position without interrupting the stator circuit, if the small auxiliary lever with which it is provided is gripped.

At the moment when zero is passed, the switch 8 is on "lower" and the master switch 9 on "hoist," so that the circuit of contactor 3 is broken and the contactor released, putting the braking resistance in circuit and thus preventing self-excitation.

Should an excessive speed be reached, either when hoisting or lowering, the centrifugal switch 7 on the motor shaft comes into action and closes the circuit of the relay 5. This relay short-circuits the rotor brushes over the resistance 6, the motor then behaving in a similar way to an induction motor. It is

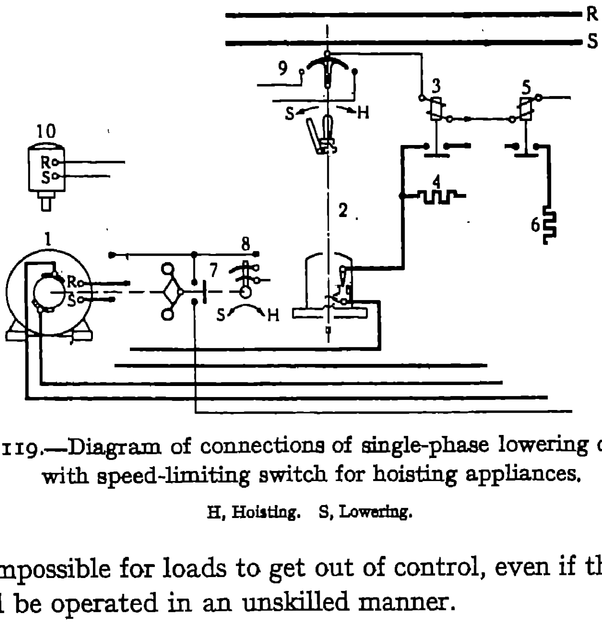


FIG. 119.—Diagram of connections of single-phase lowering control with speed-limiting switch for hoisting appliances.

H, Hoisting. S, Lowering.

thus impossible for loads to get out of control, even if the crane should be operated in an unskilled manner.

Fig. 120 shows a system of connection similar to that just described. The stator is, however, connected to the mains by a contactor, and the limit switch 11 takes effect by interrupting the stator contact circuit.

Braking is possible for both directions of rotation. For this purpose, the switch 10 has contacts for both directions, and the master switch of the controller is correspondingly constructed.

Reversing Control.—The reversing control is used for the travelling gear of hoisting and conveying plant, wherever loads have to be transported gently and without swinging.

This reversing control is extremely simple and very remarkable as regards fineness of control.

The direction of travel corresponds to the movement of the control lever, and the speed is proportional to its displacement.

Braking can be carried out quite smoothly by moving the control lever through the zero position in the opposite direction to that for travelling; the operating stand employed is combined with a stator switch. Should a limit switch be fitted to limit the travel at both ends, the controller is provided with a no-volt release so that the stator switch is opened in the event of the limit switch operating while the control lever is out of

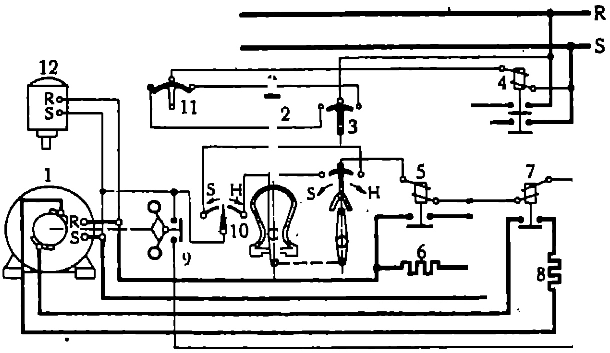


FIG. 120.—Diagram of connections of single-phase lowering control for braking in either direction of rotation. Limit switch and over-speed switch fitted.

H, Hoisting. S, Lowering.

the zero position. Before the stator switch can be closed again, the control lever must be brought back to zero.

Single-phase Commutator Motors for Operating Lifts.—Motors for operating lifts must present a certain number of special features.

When Starting.—The starting torque should not be less than twice, and not more than two and a half times the normal torque, and should be fairly constant during the starting period. The maximum starting current should be equal to 2·5 to three times normal current, and the power consumption should remain as low as possible.

When Running.—The characteristics of the motor should be those of a shunt-wound machine, with a very small speed drop

between no-load and full-load conditions. The efficiency and power factor should both be as high as possible, while the machine should have an overload capacity of about 100 per cent.

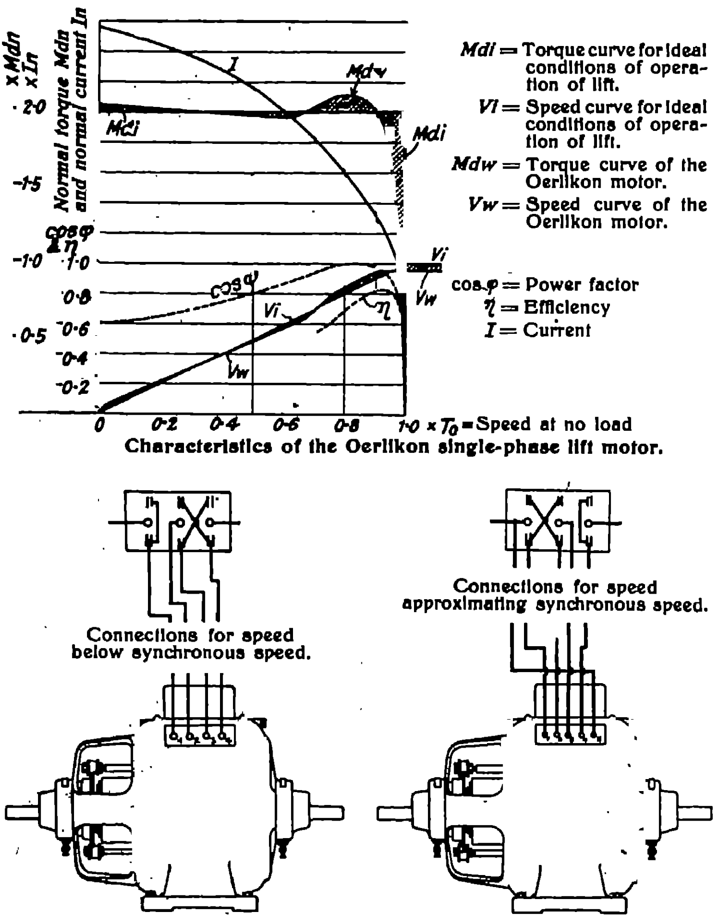


FIG. 121.—Oerlikon single-phase lift motor.

Other general requirements will be noiseless operation and sparkless running, while for obvious reasons reversing and starting should be effected by the simplest possible means. It is not usual, moreover, to use brush-shifting gear on lift motors, and the connections for starting and running should be the same. Commutator motors specially designed for lift work

fulfil these various conditions, and the performance of such a machine, built by the Oerlikon Company, is shown graphically in Fig. 121. It will be seen that the actual curves obtained only differ very slightly from what would correspond to ideal operation. Connections are very simple indeed. Such motors are usually built with four poles, and designed for 1000 to 1500 r.p.m. or thereabouts for 50 cycles. They may be wound for pressures ranging between 100 and 500 volts. Both single-phase and three-phase motors have been built for this purpose, but the single-phase type is the most commonly used. There is nothing peculiar about their construction or windings; they form just one of those types of application for which the single-phase commutator motor is eminently suitable, and are briefly mentioned as such for the sake of completeness.

CHAPTER VII.

SINGLE-PHASE TRACTION.

WHEN we are dealing with comparatively simple questions such as power stations, or industrial plants, we are faced with a certain number of definite factors from which, in view of modern scientific development, certain definite conclusions may be drawn, and design becomes a matter of detail and gradual improvement.

With railways the question is, unfortunately, far more involved. A railway is essentially a complicated undertaking, the governing factors of which are exceedingly difficult to determine.

There is, moreover, in all railway undertakings, a distinctly human element which cannot be ignored. Railways, by their very nature, are more or less of national interest and prone to what has been very aptly termed "bureaucratic engineering."

Railway electrification is as yet in its infancy, in spite of its very rapid growth. Matters are further complicated by the comparatively restricted experience of intensive electrification existing outside America. Moreover, both local and national characteristics have a very great bearing on the matter.

In the working of railways we have to deal with generators, transmission lines, converting plant, distribution lines, collection, and, finally, the driving motors themselves, and any attempt at a comparison between the various systems available must take all these factors into consideration.

When the whole of this plant is taken into account, it is unavoidable that the capital invested in a railway for electrical operation should be very considerable. For this reason electrification was confined at first to very busy lines where special traffic conditions prevailed. It is only of recent years that

electrification has been adapted to main lines, and bearing in mind the inherent complication of the problem, it is not surprising to find some considerable indecision as to the most suitable system. At first sight, the only rational method of comparing electrification systems is that based on a comparison of actual operating results obtained from statistics derived from the various types of lines already in operation for suburban or main-line traffic.

Unfortunately, such comparisons are very difficult in practice, and usually only lead to ambiguous results. For one thing, certain countries are strongly biassed in favour of one or other of the systems in question ; for another, the statistics depend far too much on the methods of compilation. A third factor of diversity is introduced by varying local conditions, and the general geographical characteristics of the country or region concerned.

From a technical and practical point of view, only two systems need be considered—the direct-current system and the single-phase system—but it is characteristic of the whole problem that supporters of either of these systems will hardly consider the other, and that biassed views are often to be found instead of an equitable and comprehensive discussion of the relative merits of both. It is not our object in these pages to discuss the relative merits of the two systems at any length, and for this we are indeed thankful. We would wish to state, however, that in our opinion there is much to recommend the single-phase system. But we hurry to add that having always been impressed with the remarkable qualities of commutator machines for use on alternating current systems, we may ourselves be biassed in this particular matter.

The final decision can only be the outcome of experience, and this is a fact that too many engineers have neglected.

The so-called weakness and limitations of the alternating current commutator motor lie, not with its inherent defects, but with its lack of development precisely in those countries where the direct-current system is preferred. The fact is significant.

There are two " schools " in railway electrification—the direct-current school and the single-phase school. England,

France, and America belong to the former ; Germany, Switzerland, and Sweden to the latter. And the particular significance lies in the fact that it is in Germany, Switzerland, and Sweden that the alternating current commutator machine has been more particularly developed. Nor was the commutator machine developed for industrial purposes as a result of its development for traction : the reverse is undoubtedly the case. There is one apparent anomaly as regards France. In France the commutator machine has been, and is being, increasingly developed for industrial purposes, and we should consequently expect this country to favour the single-phase system, whereas the opposite is actually the case. But few engineers will deny the enormous influence of American practice on the electrification of both French and English lines, and, had this not been the case, the results as regards choice of system might have been very different. There is indeed little to choose between the two : both have notable advantages and notable disadvantages, and as we have already stated, experience alone can discriminate.

In the present state of development of electric traction, the only conclusion which may be drawn is that the direct-current system appears to be more suitable for suburban lines, while the single-phase system is possibly the better of the two for main line electrification.

One of the main objections which have been urged against the single-phase system, and more generally against all alternating-current systems, is connected with the question of interference with both telephone and telegraph lines running parallel with the track.

Effective preventative devices have been devised for the elimination of this trouble, and, moreover, direct-current systems are by no means free from this complaint. Both these arguments, however, are unconvincing. There exists, and must always exist, considerable interference where telephone and telegraph lines run parallel to an alternating-current track. The remedy, a simple one, is to run such lines elsewhere. There does not seem to be any valid reason why the choice of a traction system should be influenced by telegraphic requirements, nor any outstanding difficulty in giving communication lines a route of their own—at any rate, over the greater part of the

way. In such countries as England, France, or Germany, where a vast network of roads has been developed, it is hard to find any justification for running telegraphic lines parallel to railways, especially if the practice interferes with the adoption of a more efficient system.

The so-called "battle of the systems" has been prejudicial to both, and it is exceedingly difficult to form an unbiassed opinion on the matter. The fairest method of arriving at some conclusion is to examine the reasons for which one or other of the systems have been chosen in various countries, and on various lines. The results of such an investigation are very illuminating, and one gathers that the general tendency is towards the adoption of the single-phase system, and that wherever direct-current systems have been chosen, there was some strong deciding condition extraneous to the qualities or defects of the systems *per se*. As has been already stated, the discussion centres around main line electrification; the advantages of the direct-current system for suburban lines are fairly well established and generally accepted. A brief review, therefore, of the various reasons which led to the choice of electrification systems for main line operation should give the reader a very fair opinion of the merits of both.*

The Choice of Systems.

(*a*) **Switzerland.**—The various available systems of electrification were very carefully examined both by the Investigatory Commission and by the officers of the Federal Railways.

The low pressures previously used (600-800 volts) were very obviously insufficient, and for economy the voltage had to be raised. The question became one of insulation, and it is not more difficult to insulate for 15,000 volts than for 1500, while the economy in the former case is considerable, owing to the reduced number of feeding points. Moreover, short-circuits depend on the amount of energy which can be fed into the fault, and not upon the voltage only; in this respect the use

* A complete survey of Main Line Electrification, by Sir Philip Dawson and S. Parker Smith, D.Sc., appeared in a series of articles in *The Engineer*, between June, 1924 and 1927.

of alternating current is an advantage since the natural impedance is greater than with direct current. From the point of view of efficiency, the single-phase motor is theoretically at a disadvantage, but the economy of speed regulation without resistance compensates for this drawback. The restriction in space limits the single-phase motor to 200-300 h.p. per axle, as opposed to 300-350 h.p. per axle for direct-current or three-phase motors. As regards weights, for 15,000 volt single-phase and 3000 volt direct current, there is very little to choose, the single-phase being possibly somewhat lighter. As regards maintenance costs, they are about equal for both. The number of feeding points required for direct current may be three or four times the number with single-phase. Careful study of the above considerations with reference to Swiss conditions led the Swiss Federal Railways Directorate to standardise single-phase traction at 15,000 volts and 16⅔ cycles.

The Directorate was also influenced by the good results obtained on the Loetschberg and Rhaetian Railways, and by the advisability of selecting a system with which the Swiss manufacturers were already familiar.

(*b*) **Scandinavia.**—The first post-war Swedish Commission appointed to study the problem issued its report on January 10th, 1920. The enquiry was confined to a choice between direct-current and single-phase systems. It was realised that for main line operation high voltages were required if operating costs were to be kept low. With direct current the voltage is limited practically to 3000 volts. Mercury rectifiers had not been developed up to that time for heavy railway service, so that motor generators were essential. With single-phase motors the standardised voltage of 15,000 volts for the overhead lines had proved satisfactory elsewhere for all traffic conditions. In considering the relative advantages of 3000 volt direct current and 15,000 volt single-phase, the Commission had the results of the Chicago, Milwaukee, and St. Paul Railway for the former, and their own Riksgränsen Railway for the latter. The Commission considered the systems about equal as regards interference with communication circuits.

It has been found that the energy consumption and efficiency of locomotives of the two systems are practically identical,

although for long distances between stations there is a slight advantage in efficiency in favour of the direct-current machine. The mean energy consumption at the collector bow, based on available evidence, has been taken as 22 wh. per ton-km. for single-phase, and 21·5 for direct current.

Six possible arrangements were examined in great detail, the results being summarised below :—

	Initial cost.	Yearly cost.	Per cent. yearly cost.
1. Single-phase generation at Motala : Conversion three-phase to one-phase at Trollhättan ; load equalisation at Hallsberg . . .	97·170	12·663	100
2. Three-phase to one-phase conversion in eight sub-stations, each feeding two sections . .	94·560	12·980	102·5
3. Three-phase to one-phase conversion in four sub-stations with one-phase feeders along the track .	96·350	13·046	103
4. Three-phase to direct-current conversion in sixteen sub-stations .	100·850	13·189	104
5. Single-phase generation at Motala and Trollhättan . . .	96·490	13·329	105·3
6. Three-phase to one-phase conversion in sixteen sub-stations .	98·590	13·686	108

The costs are expressed in millions of Krones, the par value being £1 = 18·159 Kr.

A detailed examination thus shows the difference between the systems to be small.

The Commission recommended the first of these alternatives. Attention was drawn to the fact that the single-phase system was better adapted for future extension, and preferable for lines where traffic was not heavy.

The experience from the Nordmark-Klarälven line showed that from the interference point of view it was possible to operate a railway of 150 km. in length with only one feeding point in the middle, and no sectionalising arrangements or other feeding

lines. Further new researches on the Svartön-Riksgränsen line showed it was possible to reduce the inductive potential on telephone and telegraph lines to a very high degree. For the above reasons the Stockholm-Gothenburg line was electrified by means of the single-phase system.

(*c*) **Germany.**—A report of the decisions on the question of system was published by the Verein Deutscher Eisenbahnverwaltungen in December, 1921. At the time this decision was arrived at, England and France had already been influenced by the direct-current developments in America, while Switzerland, Sweden, and Austria had standardised the single-phase system. Another consideration was that large three-phase power stations in Central and Western Germany installed for war purposes, were no longer fully loaded.

In February, 1921, a large number of prominent German and other engineers were called together by the Minister of Transport. They came to the unanimous conclusion that for main line electrification the straight single-phase system should be adopted as already installed in some districts at 15,000 volts, $16\frac{2}{3}$ cycles ($\frac{50}{3}$). The two most important points discussed were transmission and interference.

With regard to power transmission and generation, since the existing supply in Germany was insufficient, it was logical to adopt that system best suited to traction requirements, viz. single-phase. The transmission lines are cheaper, only two conductors are required, the switch gear is reduced, all of which tends to greater safety. The generator and transformers are admittedly more expensive. But this is not relatively important for long lines. In traction systems, a greater pressure drop can be allowed which again reduces the copper required. The single-phase system was also considered best for extension and development, and from the point of view of increased reliability due to its independence of industrial power.

From the point of view of interference, it was decided that the only safe and satisfactory method consisted in removing telegraphic communication lines to a certain distance.

The main line traction system was therefore standardised as single phase, $16\frac{2}{3}$ cycles, with a nominal contact line voltage of 15,000 volts.

(*d*) **Austria.**—The results of the investigation were set out in the report passed by the National Convention on July 23rd, 1920.

In this instance one of the determining considerations was that of speed control. The simplicity of control by means of transformer tappings with the single-phase system, as opposed to the more complicated series-parallel and field-weakening devices, was pointed out. Line voltage is restricted with direct-current operation, but with the single-phase system the line pressure is made independent of the motor voltage by the provision of a transformer. From the point of view of efficiency, this was considered to be some 6 to 8 per cent. better with direct current than with single-phase. For weight and cost of equipment, single-phase is at a slight disadvantage. The usual considerations regarding the reduced number of sub-stations for single-phase traction, and the fact that they are of the static type, were stressed, and also the lower over-all cost of transmission from power station to contact line.

For over-all efficiency between generator shaft and locomotive wheel rim, the single-phase system averages 60 to 68 per cent. against 47 to 61 per cent. for direct current. The over-all costs differ little.

The Austrian Commission came to the conclusion that the best system was the single-phase, with a mean line voltage of 15,000 volts, and a frequency of 16⅔ cycles.

(*e*) **France.**—Of the various missions which visited Switzerland, Italy, England, and the United States in 1919 on behalf of the Public Works Commission, the most important and influential was that which went to America. The following railways were examined in detail :—

- New York Central Railroad and Pennsylvania Railroad (direct current, 600 volts).
- New York, New Haven, and Hartford Railroad, and New York, Westchester, and Boston Railroad (single-phase, 11,000 volts, 25 cycles).
- Norfolk and Western Railroad and Pennsylvania Railroad (split-phase, 11,000 volts, 25 cycles).
- Chicago, Milwaukee, and St. Paul Railway, and Butte, Anaconda, and Pacific Railway (direct current, 3000 volts and 2400 volts respectively).

The conclusion of the Commission was in favour of the direct-current system at 1500 volts.

But this decision was taken because, from the investigation of the Commission, it appeared that *the direct-current systems were those that had been brought to greatest perfection in America.*

The consideration of interference with communication lines carries great weight in the report. A further consideration is that of side-rail collection versus overhead line. French engineers were convinced of the great advantage of the former over the latter system, and since the side rail is only suitable for low voltages, they were strongly biassed in favour of direct current. This is emphasised by the choice of 1500 volts instead of a possible 3000 volts. As regards sub-stations, the report points out that in many cases these contain rotary converters even where single-phase traction is concerned, and that one of the main advantages of this system, viz. the use of static sub-stations, is eliminated. But, on the other hand, whether the sub-stations are static or contain rotary apparatus, their number is still considerably reduced in the case of single-phase operation, and the advantage persists to a great extent.

It is significant, moreover, that in America single-phase railways are run on 25 cycles, and are consequently at a considerable disadvantage when compared to 16⅔ cycle lines. The considerable schemes planned for developing and interlinking French power stations on a standardised 50-cycle three-phase system, and the consequent undesirability of introducing special traction power stations and transmission lines form an additional argument in favour of direct-current operation. The report concludes by admitting that it is more than probable that at some future date the single-phase system will, when further developed, prove unquestionably superior practically, as it is already technically, but that in the present state of things the direct-current system is more developed, and therefore preferable. For a country with naturally progressive tendencies the conclusion is surprising, and the arguments singularly unconvincing.

(*f*) **United States.**—(1) *The Chicago, Milwaukee, and St. Paul Railway.*—The electrified portion of this railway constitutes the longest electrified line in the world.

The choice of system was influenced by the great success of the Butte, Anaconda, and Pacific Railway (2400 volts direct current), and also by the fact that three-phase 60-cycle power was already produced on a large scale by the Montana Power Company.

The use of single-phase equipment would have entailed the use of converter sub-stations. There was very little discussion about the matter at all, the Butte-Anaconda line serving as a model in practically every respect.

(2) *Butte-Anaconda Line.*—The line is fed by the Montana Company through sub-stations at Butte and Anaconda, which were already supplying surrounding industrial needs. This line was the earliest experiment in high-voltage direct-current work, and as such there was no discussion as to choice of systems.

(3) *The Inland Empire Railroad.*—This is a railway system used mainly for freight haulage in the thinly populated part of the Western States.

The line has been in operation since 1906 on the 6600 volt, 25-cycle, single-phase system. The choice of the single-phase system was decided upon from consideration of the length of the line and nature of the traffic. This would naturally lead to the decision for single-phase operation as high-tension direct current was as yet undeveloped. There is nothing conclusive about this choice.

(4) *Norfolk and Western Railway.*—The use of a system employing a third rail was inadvisable, as there is no private right-of-way. Heavy power demands require as high a voltage as possible, and the decision was for single-phase alternating current at 11,000 volts and 25 cycles.

The line is more particularly interesting in that it is in order to meet the conditions prevailing there that the so-called "split-phase" system was developed.

The service on this line, which is primarily a coal-carrying road operating over 3000 km., is extremely severe. Gradients are heavy and frequent, and the number of curves exceptionally high. Double traction, with a locomotive at each end, is often used, and there is consequently the question of ensuring simultaneous starting and regulation to be considered. It was thought that the normal single-phase motor would not be

sufficiently robust, and three-phase induction motors were used. These have the necessary robust qualities, and the regeneration of energy on down gradients was facilitated. Phase converters were installed on the locomotives.

This split-phase system was also applied to the Virginian Railroad, and there is little doubt that in spite of its apparent complication it has proved very satisfactory. The main objection to the system is the difficult and inefficient speed control.

(5) *New York Central Railroad.*—This is only mentioned for reference; the system is direct current at 650 volts. At the time of decision this was the only available system. This system is also in use on the Baltimore and Ohio railways, and the Michigan Central.

(6) *Other American Lines.*—The Pennsylvania R.R., and the New York, New Haven, and Hartford, are both electrified by means of the single-phase system—11,000 volts and 25 cycles—as also is the Boston and Maine R.R. The Detroit, Toledo, and Ironton R.R. has adopted single-phase traction at 23,000 volts, 25 cycles, and was opened in 1926. It would be unnecessary repetition to state the reasons for the choice of single-phase current for these various lines; they are identical with those already mentioned in similar cases.

The case of the New York, New Haven, and Hartford R.R., however, is worthy of mention. The requirements of the system were that it should be suitable for long distance extension, and would allow of the interchange of traffic with the N.Y.C. tracks, already electrified at 600 volts direct current. The single-phase system with alternating current series commutator motors was therefore chosen, since these traction units can be suitably designed to operate also on direct current.

From the above brief review of international main line electrification there is no evidence that either of the two systems predominates as regards suitability. Moreover, the further one enters into the details of the investigation, the more contradictory the results appear. One can only conclude that local conditions are an all-important factor in the case, and that, in reality, there is little to choose between the systems, the advantage being perhaps with single-phase traction for main lines, and with direct current for suburban operation.

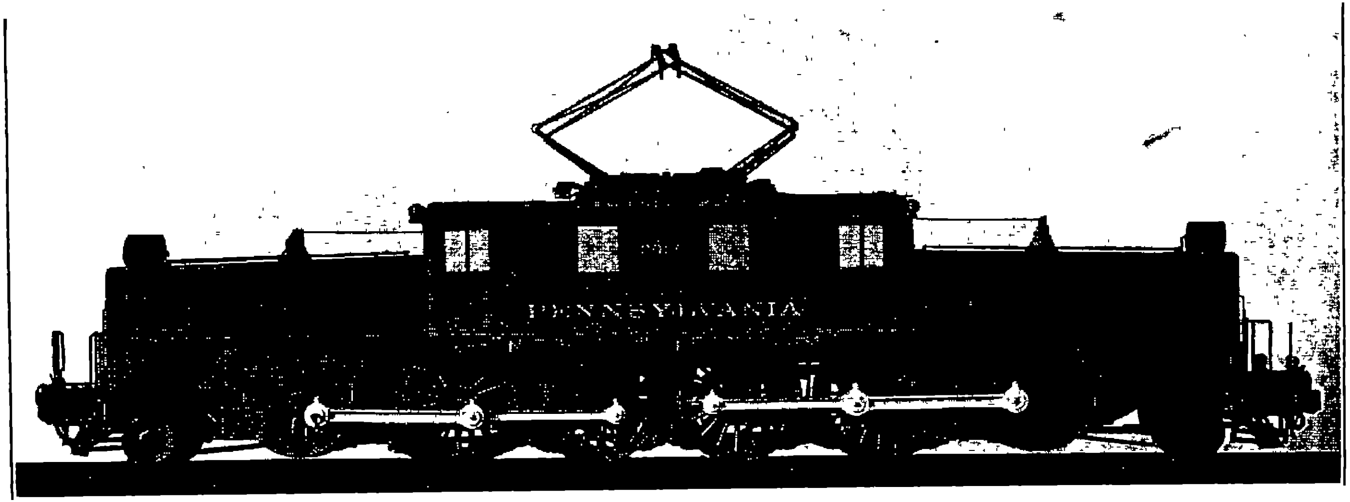


FIG. 121A.—Double-motored, single-phase freight locomotive for the Pennsylvania Railway.

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Motors.—Single-phase motors may be divided into two classes—series motors and repulsion motors. The repulsion type includes the repulsion motor proper with the Latour and Winter-Eichberg motors, the Déri motor, and other modifications involving the same principles.

Every such motor has, as we know, three windings, an exciting winding, an inducing winding, and a compensating winding. The compensated series motor is most frequently met with in traction systems, as is shown by the following summarised table :—

Swedish and Norwegian State railways	Single-phase neutralised series.
Bernese Alpine Railway	,, ,, ,,
Rhaetian Railway	15 locomotives with neutralised series.
,, ,,	9 locomotives with Déri motors.
,, ,,	1 ,, ,, series repulsion.
Swiss Federal Railways	Single-phase neutralised series.
German Federal Railways	,, ,, ,,
Austria	,, ,, ,,
America	,, ,, ,,

We need not return here to the theory of the single-phase motor, which has been fully dealt with in an earlier chapter. Certain conditions are necessary, however, for the application of these motors to traction. Both the E.M.F. in the short-circuited armature coil and the reactive component of the voltage vary as the frequency ; accordingly the frequency must be kept as low as possible. But below a certain value the transformers become unduly heavy and expensive. The usual value adopted is in the neighbourhood of 15 cycles.

The motor is larger than a direct-current motor of similar rating, and if it is designed to occupy the same space, its efficiency and robustness will suffer. Locomotives with motors carried above the under-frame, and driving groups of axles, are almost always found where single-phase is used, for the individual drive of axles imposes undesirable restrictions on the design of the motors. Finally, it should be realised that the rate of acceleration is somewhat lower with the single-phase commutator motor than with the direct-current motor. The question of traction motors being somewhat outside the scope

of the present volume, we will content ourselves with describing one of the most recent types of single-phase traction motors built to date.

Its outstanding feature, as will be seen, is the absence of any compensation windings. In fact, it is to all intents and purposes exactly similar to a direct-current motor.

Of the many single-phase motors in service, or in course of construction, the directly fed series wound motor with phase displacement in the field is now most widely used. But this most important set of single-phase motors offers many variations. Large output single-phase motors without any compensating winding must be considered a great progress in the unification of direct-current and alternating-current motor design.

The single-phase motor without compensation winding differs from the direct-current series motor only in so far as it has a laminated stator, and, moreover, is provided with a shunt resistance arranged outside the motor. This shunt resistance is in parallel with the inter-pole winding, and ensures phase displacement in the commutation pole windings with regard to the motor current. The external construction of such a motor, of 775 h.p. rating at 580 r.p.m. and 16⅔ cycles, and 700 h.p. continuous rating at 590 r.p.m. and 16⅔ cycles, may be seen from the photographs reproduced in Figs. 122, 123, and 124.

These outputs are attained according to the A.I.E.E. rules for stationary machines. When applying the A.I.E.E. prescriptions for traction material, the figures referring to output could still be increased by about 8 per cent. The motor shown in the photograph is extensively used for the individual drive of locomotives; its weight is 6200 kg.

The stator of this type of motor is built up of laminations with salient main- and inter-poles. A robust cast-steel casing serving to press and stiffen the laminations surrounds the latter.

On each pole there is mounted a main or commutation coil. The insulation of the turns consists of flexible mica. As there are no coil crossings, the space required for the frontal connection is very small. The commutation coil is in the upper part of the slot, i.e. as near as possible to the rotor in order to

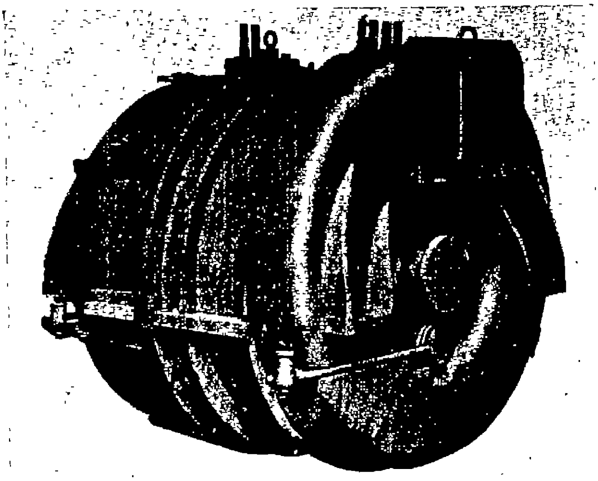

FIG. 122.—775 h.p. Brown-Boveri, 580 r.p.m., 16⅔ cycle, single-phase traction motor, external construction.

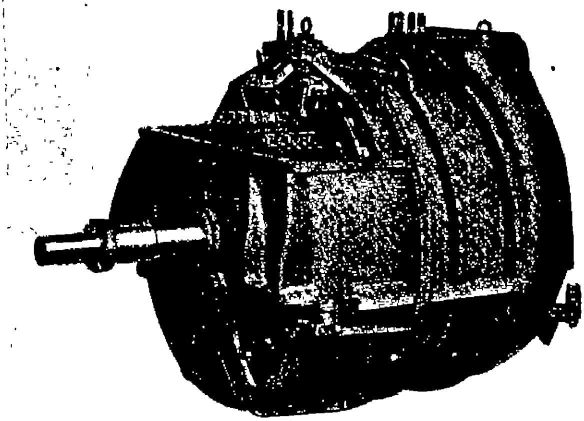

FIG. 123.—775 h.p. Brown-Boveri, 580 r.p.m., 16⅔ cycle, single-phase traction motor, external construction.

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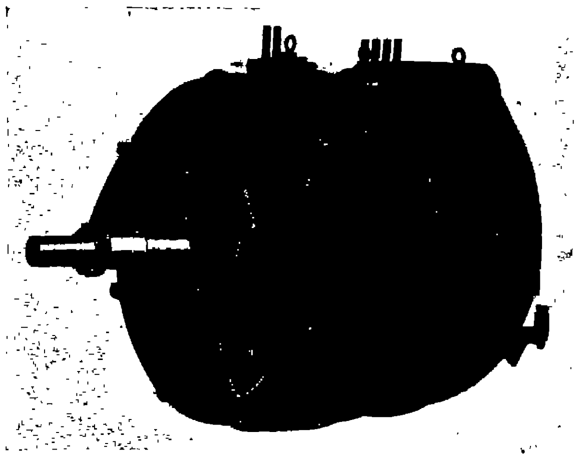

FIG. 124.—775 h.p. Brown-Boveri, 580 r.p.m., $16\frac{2}{3}$ cycle, single-phase traction motor, external construction.

[*See page* 202.

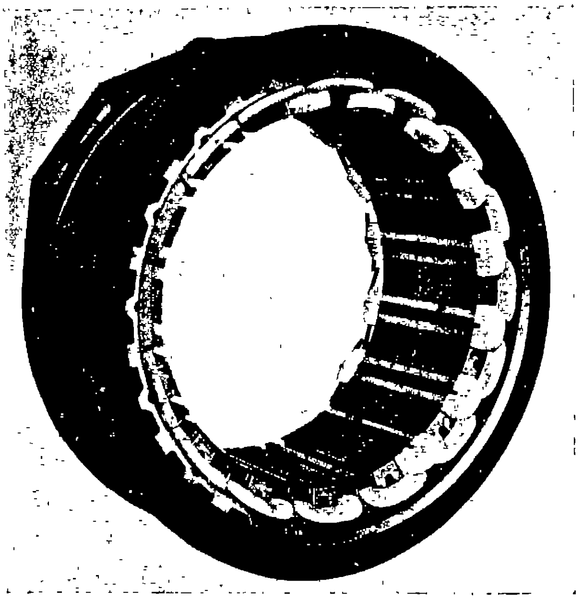

FIG. 125.—Stator winding of 775 h.p. single-phase traction motor.

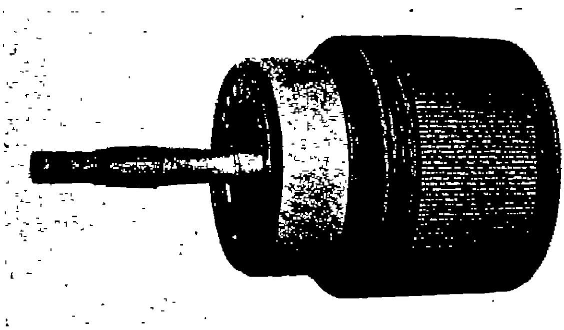

FIG. 126.—Rotor of 775 h.p. single-phase traction motor.

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obtain as small stray fields in the coil itself, and as small stray field between the rotor winding and commutation winding, as possible. A further consequence of this arrangement is that the losses of the commutation pole turn out to be smaller. The exciter coil is placed in the lower part of the slot. This arrangement is particularly advantageous if the coils are wound directly in the stator. If completely wound coils ready for insertion are used, the two windings are usually placed side by side in the slot. This arrangement is, of course, more advantageous with regard to repair work, but, on the other hand, the stray conditions are worse. Fig. 125 shows the very simple stator winding of the new traction motor.

For the construction of the rotor the usual practice has been abandoned. The slots were left open, enabling finished and micanite moulded frames to be inserted. Thus a very simple construction of rotor winding is obtained, since the insertion of the sides of the coils offers no difficulties owing to the small projection on the front side.

A large number of axial cooling ducts and slots ensure very intensive cooling of the rotor. The air escapes from the rotor between the copper connecting pieces between commutator and winding, and cools most effectively the soldered points at the commutator and at the winding. These soldered points, however, are not endangered when the separate ventilation fails, as the connecting pieces act as ventilation wings which keep the closed soldered point cool. By this method, and owing to the use of mica insulation, the rotor winding is greatly heat-resisting, i.e. it does not deteriorate with temperatures which are far above those allowed. The commutator is rather shorter than for the compensated single-phase motors, since the number of brush carriers has been increased, so that the current per row is reduced, and therefore also the length of commutator, provided the brushes are equally loaded.

The comparatively large number of poles of this motor has considerable advantages also with regard to electric characteristics. Owing to the small polar arc it was not only possible to eliminate the compensation winding, but also to obtain a smaller flux, and therefore a smaller transformer pressure. The consequence of this is that the motor has a wide and

continuously available regulating range (about 1 : 3). For the motor mentioned above, this means that the locomotives equipped with it can not only be used for express trains running at a speed of 90 km./h., but that the same locomotives are also suitable for hauling goods trains running at a speed of 30 km./h.

Besides this small transformer voltage, the increased number of poles produces a small current reversing voltage, and also the slot current density becomes smaller owing to the greater sub-division. Thus a motor is obtained which commutates excellently and in a similar manner to a direct-current machine. Torque peaks ensue when switching during the acceleration period. By the unsaturated magnetising curve and the steeper speed curve a sine-shaped current curve is obtained which

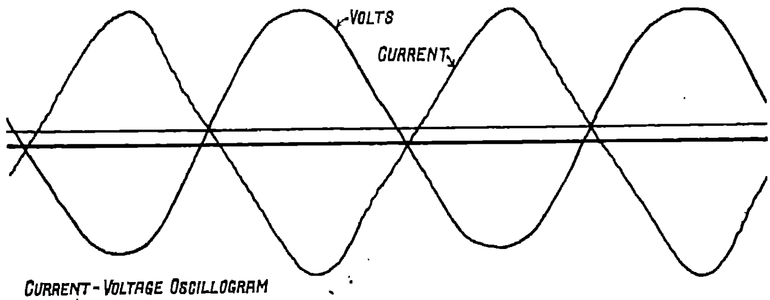

FIG. 127.—Oscillogram for 775 h.p. Brown-Boveri motor.

again leads to a better commutation, since a distorted current curve is, of course, unable to eliminate a sine-shaped transformer electromotive force in the coils short-circuited by the brushes. For this reason it is not suitable to limit the transformer electromotive force for larger currents by the saturation of the power flux path, as this is still often done. From the oscillogram of the motor (Fig. 127) may be seen the very slight curve distortion, both with regard to current and voltage. One might be tempted to conclude that by the elimination of the compensation winding and the larger number of poles, the power factor of the motor will be impaired, but this is not the case, as shown in curves (Fig. 128). Even at a one-hour rating the motor reaches a $\cos\phi = 0{\cdot}94$. In service the power factor is mostly

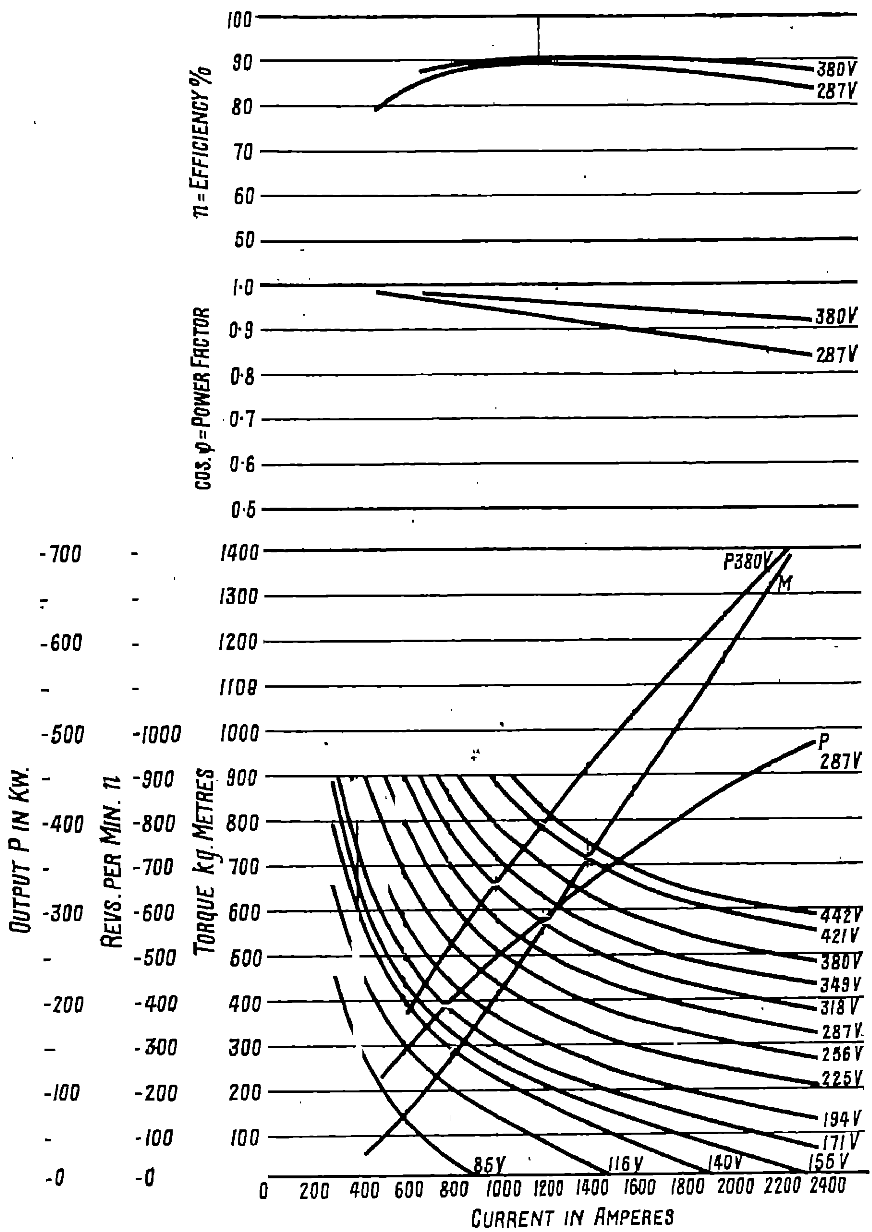

FIG. 128. CURVE OF SINGLE PHASE TRACTION MOTORS

TYPE

ONE HOUR RATING 775 H.P. 580 R.P.M.

CONTINUOUS RATING 700 H.P. 580 R.P.M.

higher, since the load is smaller and the speed higher. This, however, may easily be accounted for if one considers that the exciter winding which supplies most of the wattless voltage can be made considerably smaller for motors without compensation, as the ampere turns for forcing the main power flux through the compensation teeth can be dispensed with. This causes a reduction of the excitation of about 20 per cent. By this elimination of the saturation spot, a steeper speed curve is obtained.

The Control of Single-phase Railway Motors.—The control of the speed of single-phase railway motors is usually accomplished by varying the voltages applied. In some cases, and for certain types of motors, the control is effected by brush-shifting.

The applied voltage may be altered by tapping off varying voltages from the transformer, or by means of an induction regulator, the former method being more generally applied for reasons which will be duly dealt with.

The speed control of these motors differs essentially from that of direct-current motors in that :—

(1) There is no loss in resistances during control.

(2) Each control point becomes a running point, with a definite characteristic curve as would be the case for a new brush-setting.

The latter point will be easily understood from the theory of the single-phase commutator motor which has already been given, and its importance will readily be appreciated in connection, for instance, with the control of freight locomotives. Such locomotives, where direct current is used, are quite generally provided with rheostats with five-minute rating, and frequently under severe operating conditions, continuously rated rheostats are installed.

It is the general practice to equip all single-phase locomotives with transformers, whether the control is by brush shifting or voltage regulation, since the transformer enables the motors to be fed at a relatively low pressure, a desirable feature for good operation. Series motors of moderate output are thus supplied at a pressure of 250 to 350 volts ; series motors of larger output at a pressure of 400 to 500 volts ; repulsion motors at a pressure of 750 to 1000 volts The secondary

winding of the transformer is also supplied with tappings from which auxiliary motors for compressors, blowers, etc., are fed at 100 or 220 volts. Lighting and heating circuits are fed from similar tappings.

The method of speed control by voltage variation, where transformer tappings are used, is very similar to the contactor system for controlling continuous-current motors. It is more widely used in practice than voltage regulation by means of induction regulators. The induction regulator method has, it is true, a number of advantages, such as the elimination of contactors, the maintenance of which is a heavy item. Moreover, a very fine gradation of voltage is possible, so that a perfectly uniform torque can be obtained throughout the accelerating period. On the other hand, it has defects which are very serious as far as locomotive work is concerned. The regulator is heavy, bulky, and costly. On account of the air-gap, the magnetising current will be comparable with that of an induction motor of the same rating, and this magnetising current will be supplied by the transformer, and, consequently, the power factor will be lower than would be the case if contactors were used. For these reasons, and in spite of the advantages of the induction regulator, the transformer-tapping and contactor method of control is more generally used.

The fundamental difference between contactor operation for direct-current regulation and that for alternating-current control lies in the fact that, in the latter case, the contactors being connected to the various tappings of a transformer, when these are successively closed, precautions must be taken to avoid short-circuiting the various sections of the transformer winding.

Obviously, the simplest way of doing this is to open the motor circuit in passing from notch to notch, but this method is never used, as it produces jerky acceleration and arcing at the contacts (Fig. 129).

A second method of transition involves the use of a preventive coil. This consists of a laminated magnetic circuit wound with a single winding tapped at the centre-point. Such a coil will offer a high impedance to an alternating current passing through it from end to end, but practically none to a current passing between the centre-point and the two ends,

since the resultant ampere turns will then be zero. The con nections are shown in Fig. 130. The contactors are arranged i two groups—1, 3, 5, and 2, 4, 6. The connection of the moto is taken from the centre of the preventive coil. One contacto of each group, connected to adjacent tappings, is closed on eac notch. The motor is then supplied at a voltage midway betwee the two tappings, but the current to it passes through the pre ventive coil in such a way that no choking effect results. T increase the voltage, for instance, the motor being supplie from contactors 1 and 2, number 1 is first opened and number is then closed. The preventive coil constantly remains as high impedance across the transformer section between 1 and 2 or 2 and 3. The motor is constantly supplied during accelera tion, and no jerks or arcing can occur. During the transitio period the full motor current is carried by one contactor an

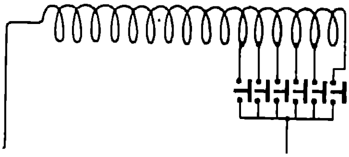

FIG. 129.—Simple contactor controller.

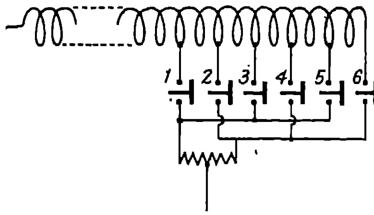

FIG. 130.—Contactor diagram with preventive coil.

half the preventive coil, but since such transition periods ar necessarily of short duration, there is no fear of over-heating.

The choking effect of the half coil will also influence the moto voltage during the transition period to a certain extent, bu this is relatively unimportant for the same reason.

A third method has been developed by Siemens-Schucker which involves the use of a double secondary winding on th transformer and two preventive coils. The method will b understood by referring to Fig. 131. The motors are connecte together in two groups. Under normal conditions two con tactors, one in each group, are closed. The motors and trans former windings thus form a closed series winding. Th tappings of the two secondary windings are arranged to giv unequal voltages, and the voltage on the motors is equalise by the two cross-connected preventive coils, which are wound

on a common core so that they can act inductively on one another.

To increase the voltage, for instance, suppose contactors 3 and 4 are closed, 3 is opened and 5 closed. During the transition period both motors are supplied from one secondary winding, the motors being in parallel with a preventive coil in series with each. As the preventive coils are both wound on the same core, the resultant ampere turns will be zero, so that these coils have no choking effect.

It will be seen from the above brief examination that the control of single-phase motors is extremely simple, and compares very favourably in this respect with the control system usually employed for direct-current motors. While this simplicity is a very notable advantage, it is well to bear in mind those other no less important points which have already been mentioned, viz. there are little or no losses during speed regulation, and every point is a running point.

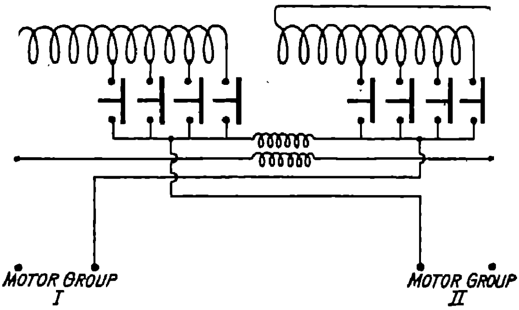

FIG. 131.—Siemens-Schuckert control with double secondary winding and two preventive coils.

As has been already stated, the contactor and transformer tapping method is the more popular of the two, and we will limit our examination more particularly to this system.

The system of control, generally, is similar to any system where contactors are used. A master controller is employed, and the contactors may be operated pneumatically, or electro-pneumatically, or electrically.

If they are operated electrically or partially electrically, the current may be supplied from tappings off the main transformer, from a separate transformer, from a motor generator set, or from a storage battery. When direct current is used as a source of energy, the contactors do not differ in any way from the usual form of contactor used for direct-current work. When

alternating current is used, however, a certain number of features must be incorporated in the design for the purpose of obviating the difficulties that arise from the use of a fluctuating current which is, moreover, at a low frequency.

The iron core, and the plunger, must of course be laminated, and the voltage applied to commutator motors being relatively low, the contacts should be amply proportioned, as they will have to deal with quite heavy currents.

In order that there may be no possibility of short-circuiting any of the transformer sections, some interlocking device is provided. This is usually electrical, and takes the form of auxiliary contacts, but a mechanical device is used in some cases. The plunger is so designed as to keep out of actual contact with the pole-face of the core, in order that a quick release may be obtained. For the same reason the plunger is usually rather heavy, and where this is not the case, a demagnetising coil is sometimes fitted.

One of the main troubles which has to be overcome when dealing with alternating-current contactors is that known as "chattering": with the low frequencies in use on traction systems, this effect may be very serious. It is quite simply overcome by the use of a "shading" coil. This consists of a short-circuited coil, often a copper strip, inserted in the face of either the plunger or the pole piece (Fig. 132). This coil produces an irregular two-phase magnetic field, and in consequence the pull is practically constant.

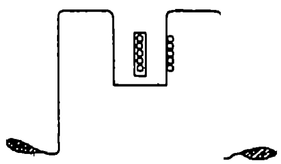

FIG. 132.—Plunger and pole piece of low-frequency contactor showing "shading" coil.

A characteristic feature of all alternating-current contactors is the automatic reduction of the current in the operating coil as the plunger is pulled up. When the coil is connected to an alternating current of constant voltage, the flux in the core must remain constant irrespective of the position of the plunger. But the ampere turns required to produce this flux are proportional to the reluctance of the magnetic circuit. The maximum reluctance occurs when the plunger is out, the minimum re-

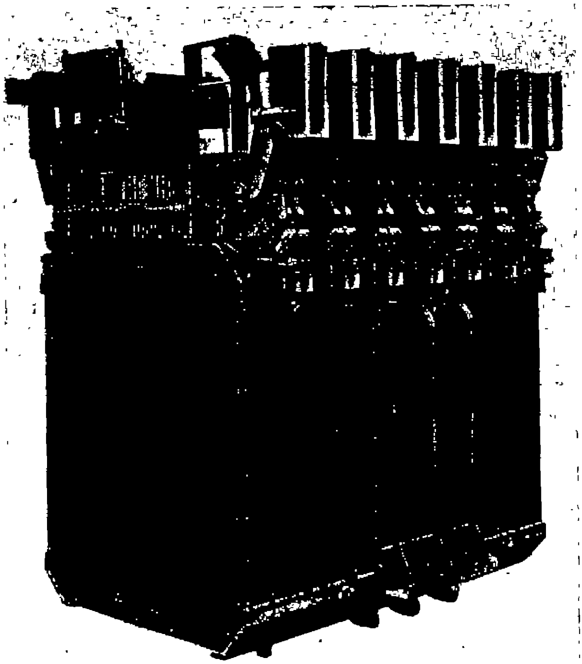

FIG. 133.—1650 k.V.A., 15,000/350 volt transformer with built-on switch gear, by the Bergmann Electricitäts Werke A.G.

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luctance occurs when the plunger is pulled in, and the ratio of maximum and minimum currents will depend, therefore, on the stroke of the plunger and may be of the order of 5 to 1.

The contactors are usually built on to the top of the transformer; a typical group of this type is shown in Fig. 133.

The photograph reproduced shows a 1650 k.V.A. 15,000/350 volt transformer with built-on switch gear built by the Bergmann Electricitäts Werke A.G. for the Magdebourg-Leipzig-Halle locomotives on the German State Railways (see description, p. 226). The particular contactors shown, in view of the high motor current to be handled, are operated by compressed air.

In some cases the contactors are replaced by a rotary drum type controller. The main cylinder is moved to the respective notches by means of a small continuous current motor in conjunction with a ratchet wheel and two electrically operated pawls.

The master controllers, for single-phase operation, are similar to those used for continuous current multiple-unit control systems, except that no transition notches are required, and on account of the low voltage of the control circuit it is not necessary to provide blow-out coils.

The control of brush-shifting motors of the Déri type is carried out directly from the controller through suitable gearing, and the controller takes the form of a hand-wheel. This method of control has not as yet been developed for multiple unit operation. All types of series, compensated-repulsion and doubly-fed motors require reversing switches to enable the direction of rotation to be reversed. Such a reverser is not necessary with the Déri brush-shifting repulsion motor, as reversing is obtained in this case by reversing the direction of movement of the movable brushes.

The reverser may consist of a group of four contactors, or a throw-over drum-type switch.

Methods of Transmitting Power to Driving Wheels.—With regard to this particular aspect of locomotive design, we have already stated that locomotives with motors carried above the under-frame and driving groups of axles are nearly always found where single-phase traction is used. The discussion of the innumerable types of drive to be found in various countries

would be entirely outside the scope of this book. Some idea of the variety of drives adopted for single-phase work may, nevertheless, be gathered from the accompanying illustrations. The side-rod locomotive has been very largely developed on the Continent, and its main object is to enable one or two large motors to be used instead of a number of smaller ones. The motors are then located inside the cab, and drive the wheels from the outside by means of cranks and side-rods, a suitable number of wheels being coupled together to give the requisite adhesion. These types of drive have been developed to a great extent specially for single-phase operation. The flexible gear drive has also been developed for single-phase motors, and has many points in its favour, since it tends to overcome vibration due to the pulsating torque, and in such cases the gear-wheel is mounted on a quill and drives the wheel through springs, the motor being supported from the truck frame and centred on the quill.

Any type of drive which is suitable for use with a small number of motors, or with one large motor, will, as a rule, be the most suited to single-phase work.

Locomotives.—As typical examples of single-phase machines, it is proposed to describe :—

(1) A locomotive with two motors of average rating driving coupled wheels by means of a side-rod and gear, or mixed gear and rod drive.

(2) A locomotive with an individual axle drive and flexible gear coupling.

(3) A locomotive with a single 3000 h.p. large single-phase motor and side-rod drive.

(4) A typical single-phase motor coach.

Type I. Description of a Recent Typical Single-phase Locomotive.—As a typical example of a modern express single-phase locomotive, we propose to describe the 4-6-2 electric locomotives built by the Maschinenfabrik Oerlikon, and recently put into service on the Swiss Federal railways.

The locomotives have been designed to haul train loads of 480 tons at 56 m.p.h. on gradients of 1 in 100. The latter rating can be increased by 20 per cent. for a period of fifteen minutes. Another condition is that the locomotives must be

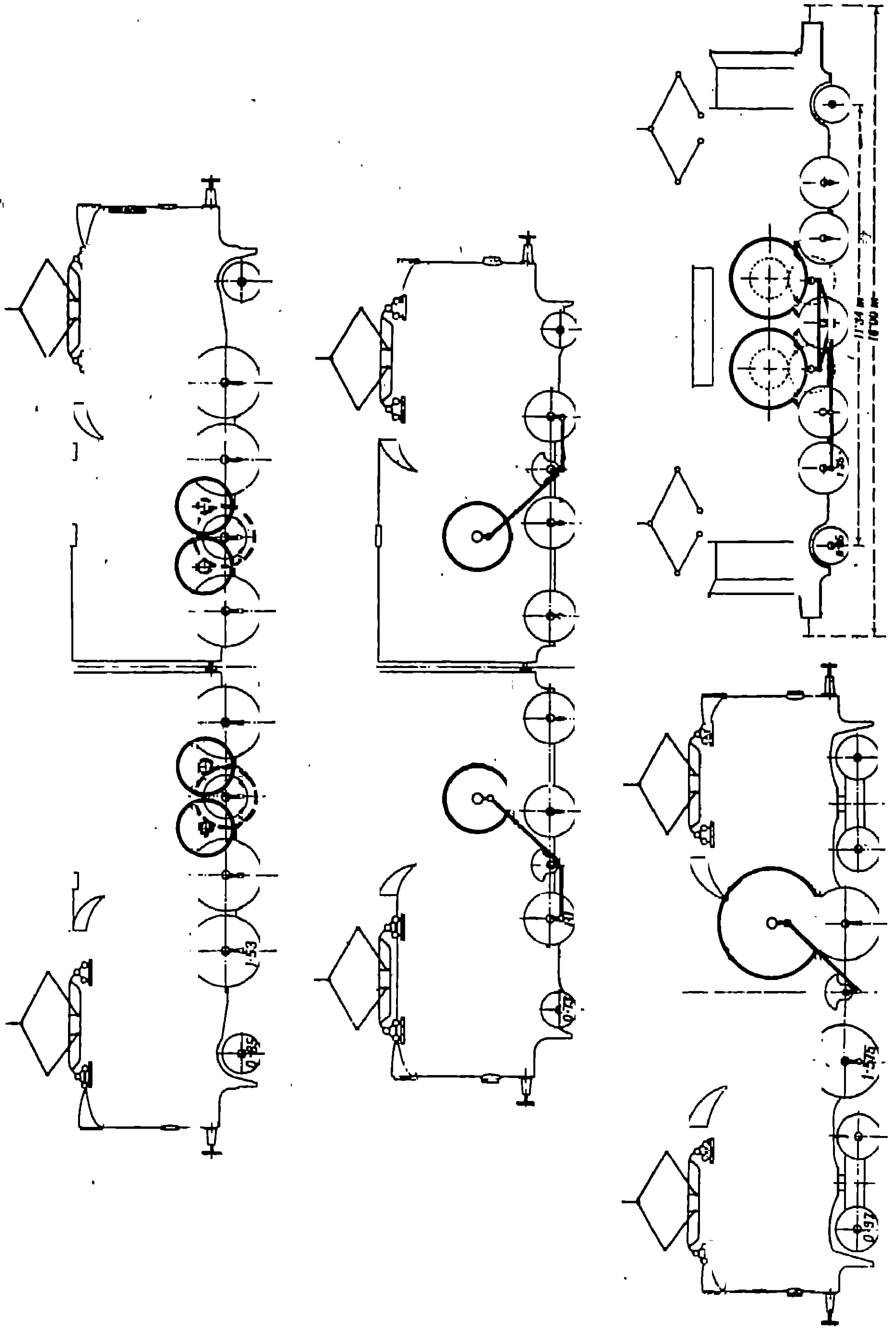

CHART 7.—Various methods of transmitting power to driving wheels.

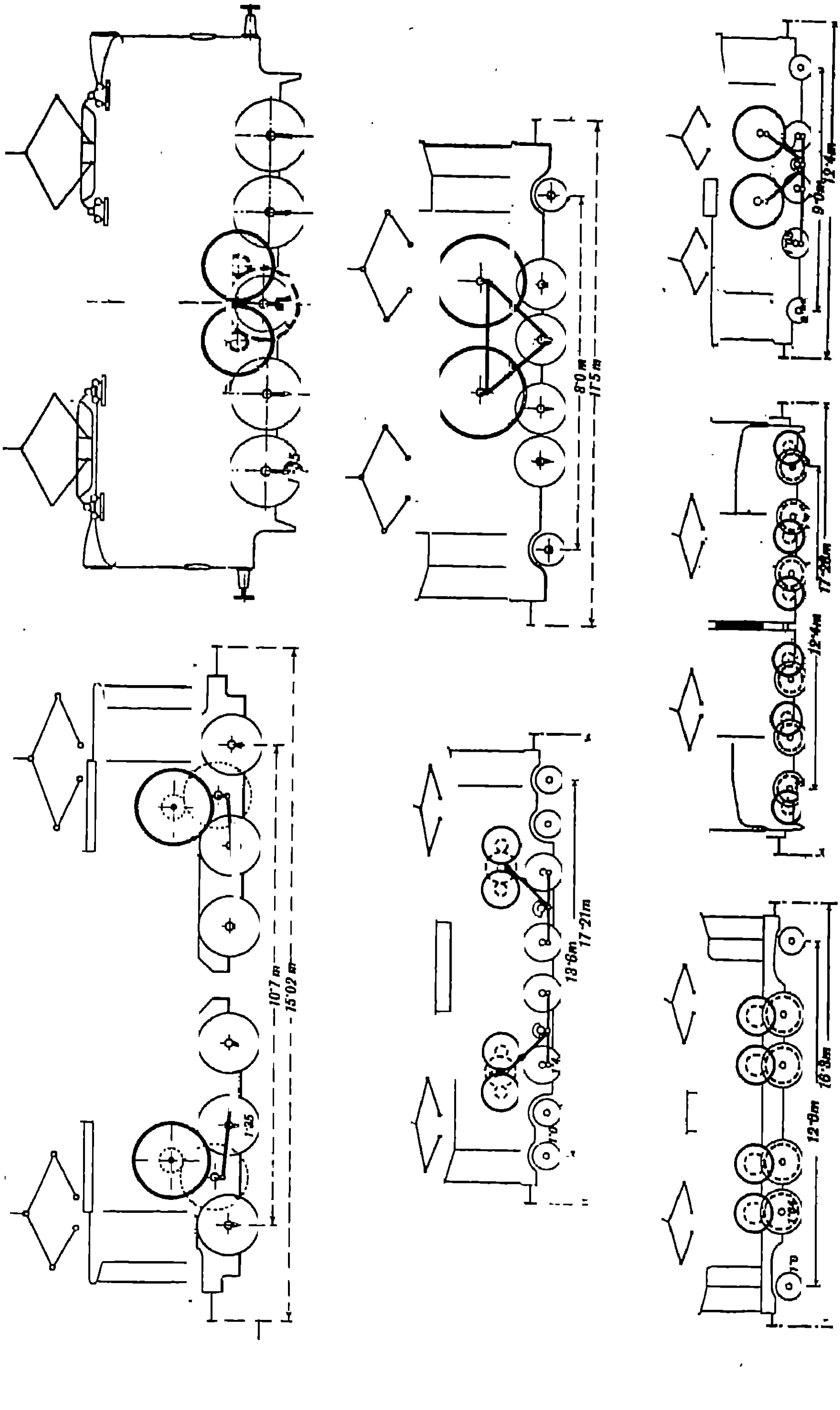

CHART 8.—Various methods of transmitting power to driving wheels.

able to make the three journeys between Zurich-St. Gallen and Zurich-Villeneuve in ten hours and eleven and a half hours respectively, hauling 480 tons, a wait of fifteen minutes at each end being included in these times. The first locomotive of the

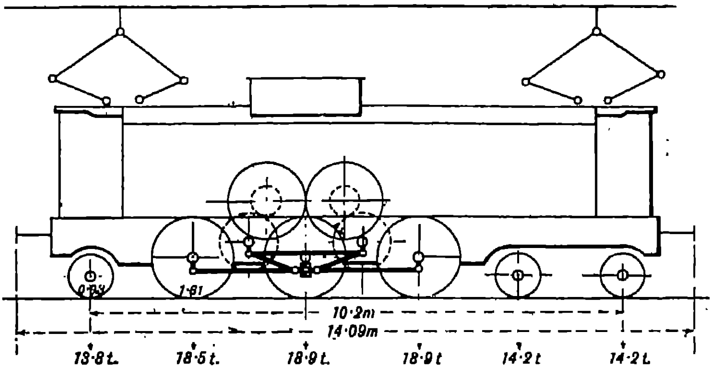

FIG. 134.—Diagram of electric locomotive by the Machinenfabrik Oerlikon, type with two motors, side rod and gear.

series, on which the design of these later and improved ones is based, has been in service since 1919 with excellent results. One of these locomotives is equipped for regenerative braking for use on the St. Gothard line, on gradients of 1 in 38·5. Leading particulars of the new locomotives are as follows :—

Gauge	1·435 mm. (4 ft. 8½ ins.).
Length over buffers	14·090 mm. (46 ft. 2¾ ins.).
Total wheelbase	10·800 mm. (35 ft. 5⅛ ins.).
Wheelbase of bogie	2·150 mm. (7 ft. 0⅝ in.).
Fixed wheelbase of driving axles	4·700 mm. (15 ft. 3⅜ ins.).
Diameter of driving wheels	1·610 mm. (5 ft. 3⅜ ins.).
,, ,, uncoupled wheels	930 mm. (3 ft. 0⅝ in.).
Crank circle diameter	600 mm. (1 ft. 11⅝ ins.).
Gear ratio	1 : 2·224.
Maximum height of main casing (excluding central dome)	3·750 mm. (12 ft. 3⅝ ins.).
Maximum width	2·950 mm. (9 ft. 8⅛ ins.).
Trolley wire voltage (+ 10 per cent. to 15 per cent.)	15,000 volts.
Frequency (± ½)	16⅔ cycles.
Continuous output at wheel rim at 70 km. (43¾ miles) per hour	1920 h.p. (metric).
One-hour output at wheel rim at 65 km. (40⅜ miles)	2200 metric h.p.

Tractive effort at rim, 1 hour output	9100 kg. (20,020 lbs.)
Maximum tractive effort at rim	16,700 kg. (36,740 lbs
Maximum speed	90 km. (56¼ miles).
Weight of mechanical parts	54 tons.
Weight of electrical parts, including current collectors and compressor set	40 tons.
Weight of inventory	0·6 tons.
Weight of locomotive in running order	96 tons.
Adhesive weight of locomotive	56 tons.

Two motors, attached solidly to the frame and to e other, each drive a countershaft through two sprung pin with helical teeth (see Fig. 135) : the latter, taken on the sides, together form a chevron gear. The countershafts also as crankshafts, power being transmitted thence to driving wheels by a triangular yoke and coupling rods. feet of the motors rest on cast-steel longitudinal girders un the motors, so that the central portion of the frame form rigid whole.

The box-casing of the locomotive is divided internally so to form a central machine-room with a driver's cab at each e The machine-room is further divided for purposes of ventilati

For a number of years the Swiss Federal Railways ha steadily increased the number of standardised components the locomotives employed. Capital and maintenance co have thus been reduced, and operation has been simplifi The general arrangement of the electrical equipment is dicta by the central position of the motors. In front of the mo room are situated the main switch and train-heating contr the step-down transformer with tappings, and the step by st regulating switches. The space between the latter, for t inspection of the switches, is reached through a door in t driver's cab. Between the rear cab and the motor room a the oil circulating and cooling set for the transformer, a bui on motor generator, and the compressor set. There are al in this compartment the direct current, alternating current, a relay switchboards, and the automatic controller for the com pressor. In the roof superstructure over the motor room a the switching choke coils, the shunting resistances for t auxiliary poles of the driving motors, and, in the case of t locomotive with regenerative braking, the braking choke coi

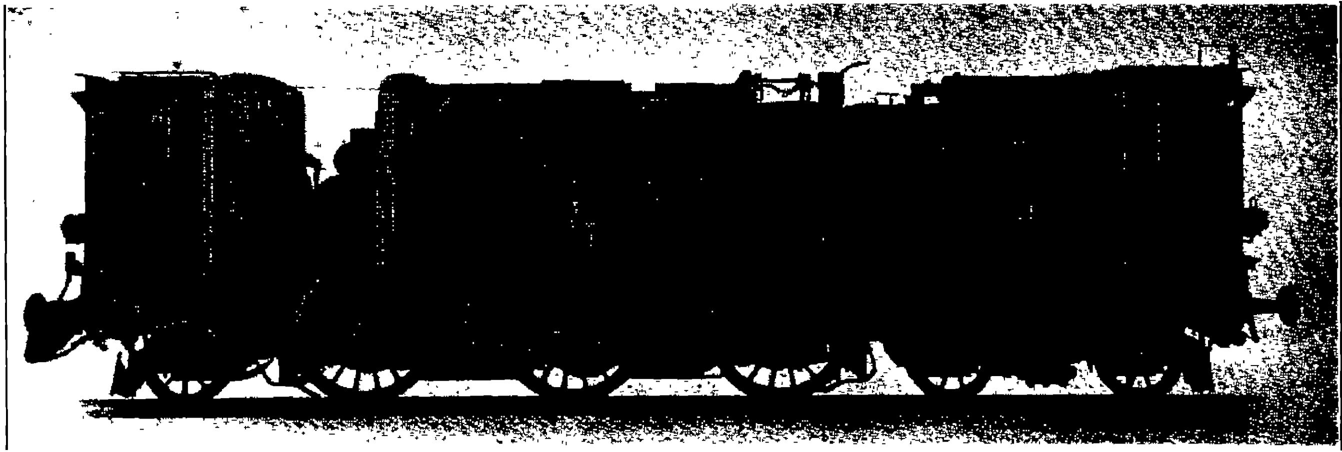

FIG. 135.—Single-phase express electric locomotive built by the Maschinenfabrik Oerlikon.

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Current is collected from the overhead line by means of two pantograph frames actuated by compressed air. When fully elevated the contact surface of the bow is 2·7 metres (8 feet 10 inches) above its position when completely lowered. An air-throttling cock ensures that the pantograph descends smoothly and without shock, whilst an outlet valve in the pipe to the pantograph cylinders permits rapid escape of air from the supply pipes, thus avoiding the delay in lowering which would occur if the compressed air had to flow back through the whole pipe system. Isolating switches and emptying cocks are provided, so that each current collector can be put electrically and pneumatically out of action.

The main switch in the first thirteen locomotives is of the older type with single break and pneumatic operation, but in the remaining locomotives a motor-operated multiple break switch is employed, and provision is made for the manual operation of this switch from the cab in case of need. Both types of switches have auxiliary contacts which place buffer resistances in circuit before the main contacts close. An earthing switch is interlocked with the various parts concerned, so that it is impossible to obtain access to the interior of the main switch until the pantographs have been lowered, and both poles of the switch connected to earth.

The main transformers are of the core type, with a vertical core and concentric coils in two of the locomotives, and with a horizontal core and pancake coils in the later locomotives.

In the first group the transformers have separate primary and secondary windings, but those in the second group are connected as auto-transformers. This change in the construction of the transformers is due to the attempt to utilise more fully the overload capacity of the motors while reducing the weight of the transformer and locomotive. Tappings on the low-tension windings provide pressures up to 536 volts for the main motors. A flexible pipe between the transformer tank and a cowl in the roof carries oil-vapour into the open air and prevents the formation of explosive mixtures inside the locomotive casing.

The main regulating switches, of which there are two on each locomotive, are built as a compact series of switch levers

actuated by cams. They consist of two halves, mechanically connected but electrically insulated from each other, each relating to the corresponding limb of one of the two switching choke coils. The two step switches of each locomotive can be operated by electric motor or by hand, and they work alternately so as to reduce the power required—an important consideration where manual operation is concerned.

The reversing switch of locomotive No. 10401 with regenerative braking is operated electro-pneumatically, but manual control through rods is used on all the later locomotives.

Main Motors and Auxiliaries.—As in all the single-phase locomotives yet delivered by the Oerlikon Company, the main motors are compensated series motors with out-of-phase auxiliary fields. They are fitted with a 16-pole winding; the diameter of the commutator is 950 mm. (37·4 ins.); and the weight of each motor, including the pinion, is 10,550 kg. (23,210 lb.). On the one-hour rating each motor develops 1100 metric h.p. (1085 h.p.) at the rims of the driving wheels when the terminal pressure is 400 volts. The direction of running is reversed by reversing the current in the field winding. A new feature in the construction is the arrangement of the main and auxiliary field windings. These are former-wound coils, placed in the stator core and secured by wedges which serve also as cooling ducts.

Special care is devoted to the circulation of cooling air through the stator and rotor. A ventilating set, consisting of a motor-driven fan mounted above and between the two main motors, draws air through louvres in the side of the locomotive casing, forces it through the motors, and expels it into a partitioned-off space on the commutator side of the machines, whence it escapes through the louvres in the roof.

The transformer oil is circulated and cooled by means of an auxiliary set, which comprises a centrifugal pump and fan (both driven by the same motor) and a tubular cooler mounted at the side of the fan. Air is drawn from the interior of the locomotive, through the cooler, and discharged on to the track through a diffuser. Special baffles are fitted to deflect the outcoming air and prevent the raising of dust at level crossings. The oil pump absorbs 2½ h.p., and handles about 55 gallons of

oil per minute. The fan absorbs 11½ h.p. at 1800 r.p.m., and deals with 5300 cub. ft. of air per minute at a total pressure of 6¼ in. water gauge.

Compressed air is produced by rotary compressors in the older locomotives of the series and by reciprocating compressors in the later machines. The reciprocating compressors are driven by high-speed electric motors through 1 : 3 gearing, and compress 70 cub. ft. of free air per minute to seven atmospheres (105 lb. per sq. in.).

Driver's Controls and Protective Devices.—The driver's control gear, in each cab, comprises a complete apparatus with mechanically interlocked master switches for operating the pantographs, main switch, reversing switch, and regulating switch; also measuring instruments for the line voltage, high-tension current, and current through each main motor. The interlocking is such that when the pantograph control lever is put in the off position the rest of the controller is completely blocked. Provision is made for testing, without risk, the correct working of the various parts of the control equipment when the pantographs are lowered. There are also electrical interlocks to prevent the driver from closing the main switch unless the regulating switches are off.

The various auxiliary switches, fuses, trip relays, ammeters, and voltmeters for the train heating and battery circuits, and the automatic starting gear for the motor generator set, are arranged on five switchboards, two being in the cabs and three on the partition between the compressor room and the main motor room. All cables and terminals on these boards are labelled to correspond with the complete wiring diagram.

As protection against overloads and short-circuit, there are provided a maximum current relay with time element for the high-tension current circuit, and three instantaneous overload relays for the main motors and train-heating circuits respectively.

The locomotives of this series already in service have given very satisfactory performance, the smooth running over curves being particularly noticeable. In whichever direction the locomotives be driven, they take curves without shock or vibration, owing greatly to the arrangement of the springs and points of

support, and partly to the concentration of weight towards the centre of the locomotive, high on the frame. The driving gears and mechanism also operate smoothly and steadily at all speeds, and from the electrical standpoint the locomotives have met all requirements.

Type II. Single-phase Electric Locomotive with Individual Axle Drive.—As a contrast with the former type of side-rod locomotive it is interesting to examine another locomotive, of less recent date, built by Brown-Boveri for the Swiss Federal Railways (see Figs. 136 and 137). This is an express passenger locomotive, and its leading feature is the individual axle drive devised by the makers. The majority of locomotives equipped by this firm have a side-rod drive, but comprehensive re-

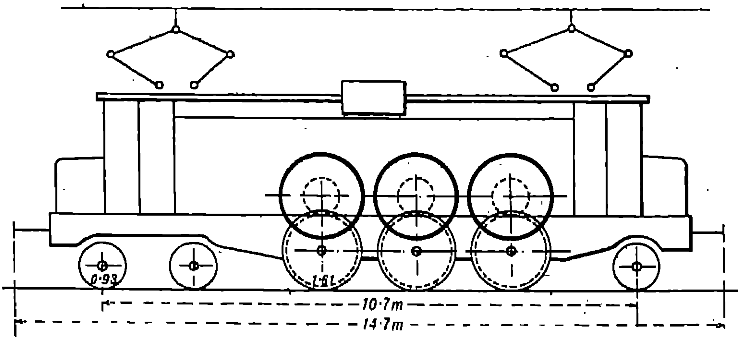

FIG. 136.—Diagram of electric locomotive by Brown-Boveri, with individual axle drive.

search and careful examination of the service conditions have shown that this class of drive is not always the most ideal means of transmitting power from the motor or from its gears to the driving wheels.

The side-rod drive undoubtedly affects the smooth running of a locomotive, and has, moreover, a detrimental action both on the bearings and the commutator of the single-phase motor. A further disadvantage of this class of drive is that it allows a certain relative displacement in the direction of rotation between the motor and the coupled wheels.

The locomotive is supported on twelve wheels, the three pairs of driving wheels being placed between a four-wheeled bogie truck at one end, and a two-wheeled pony truck at the

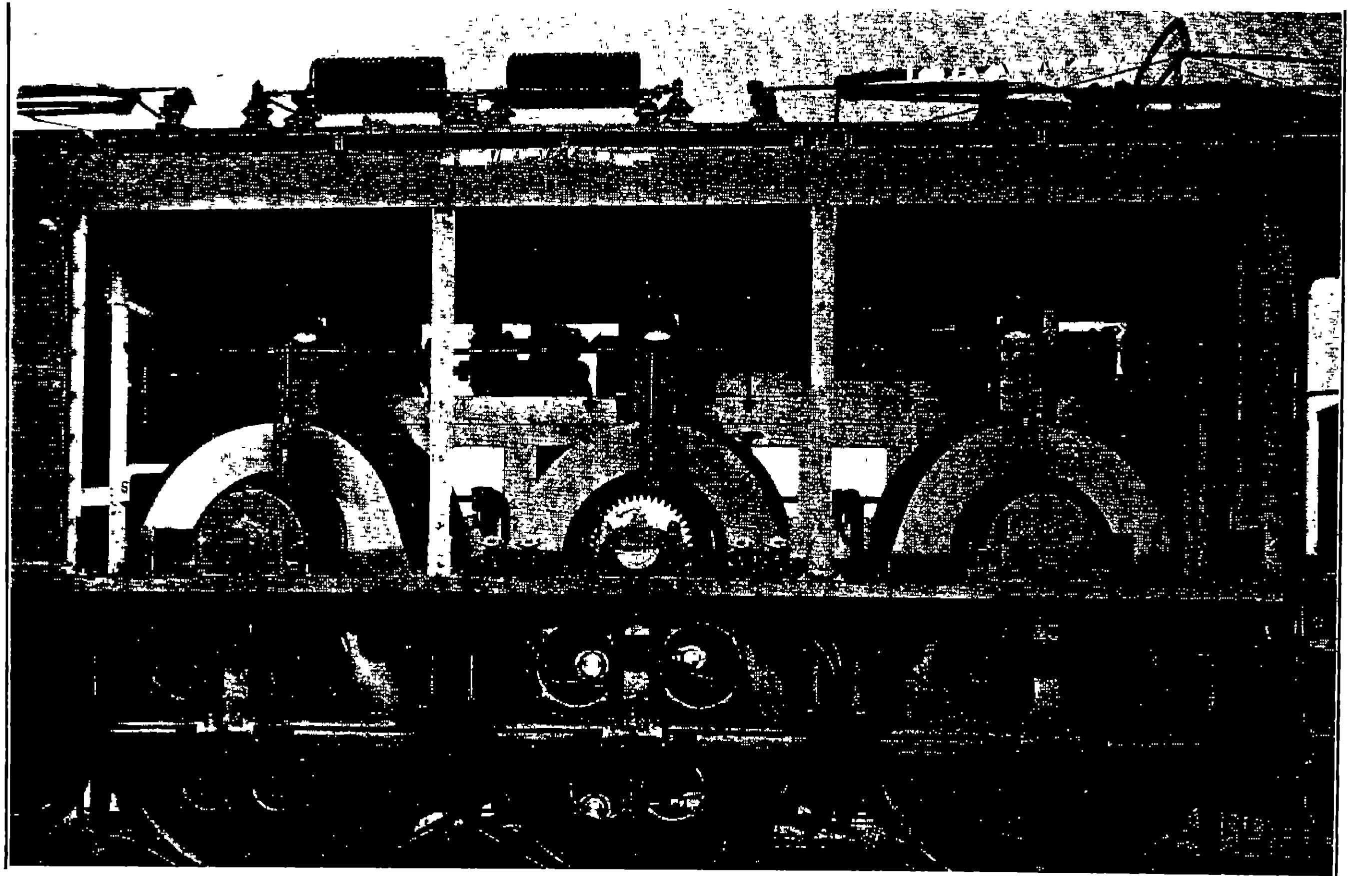

FIG. 137.—View of Brown-Boveri locomotive from driving side with body plating removed.

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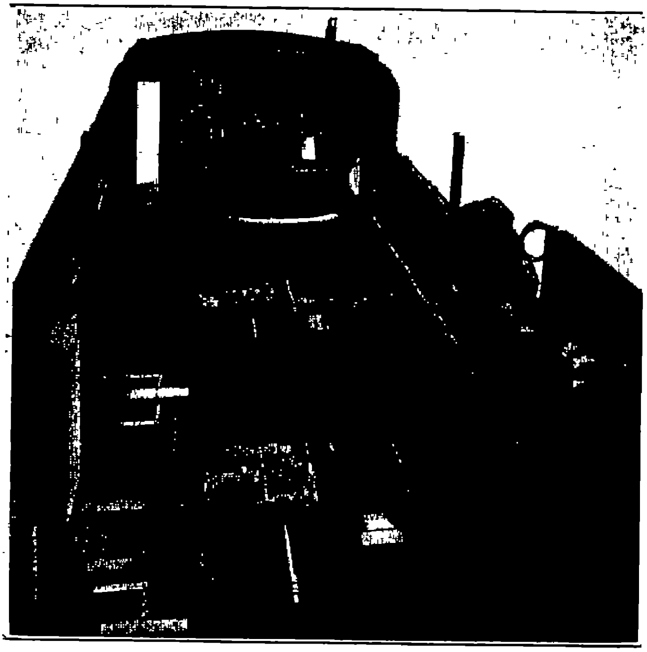

FIG. 138.—View of Brown-Boveri locomotive showing motors and transformer.

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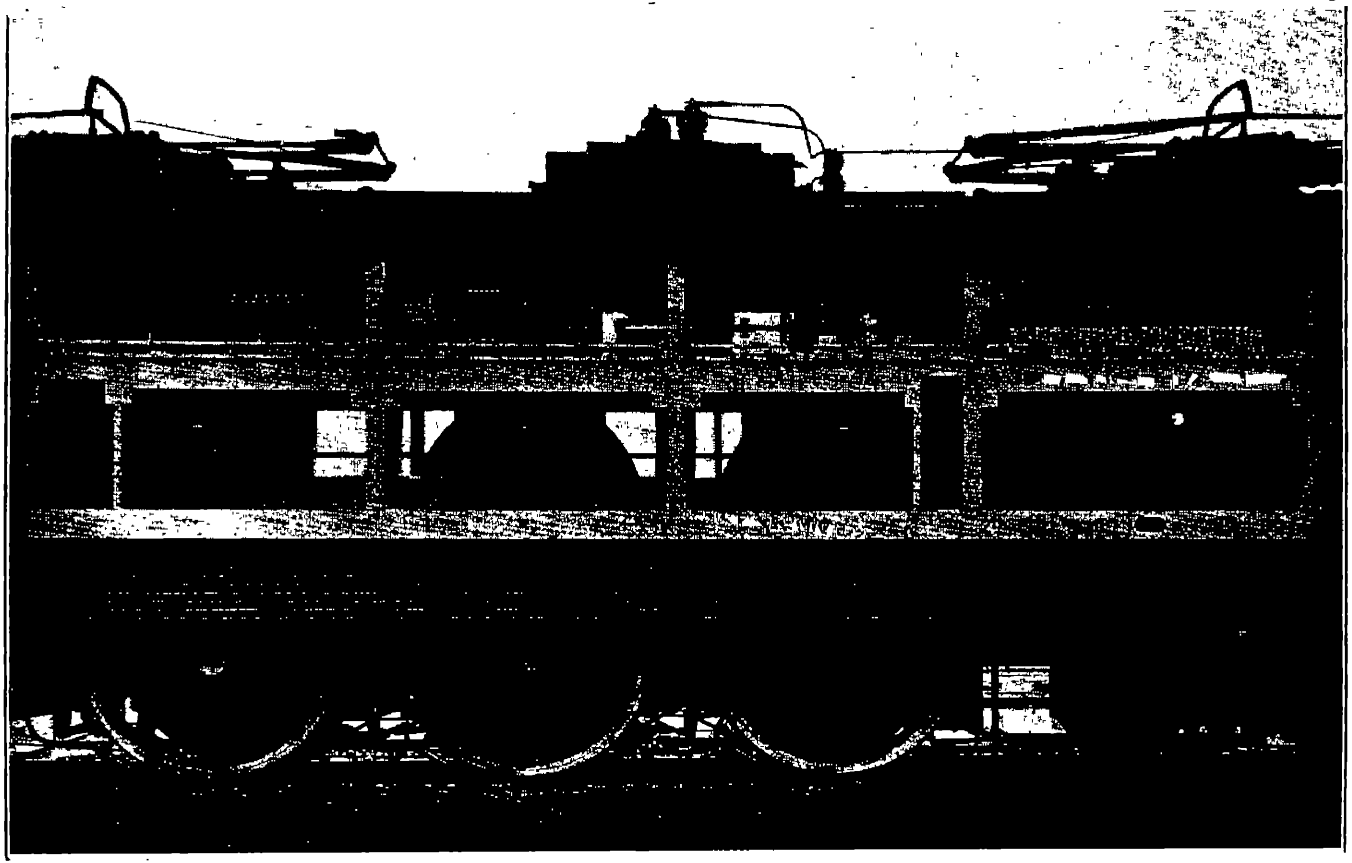

FIG. 139.—View of Brown-Boveri locomotive on reverse side to driving side.

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other. The prescribed maximum speed is 55 m.p.h., and the locomotive weighs 90 tons, the allowable axle loads being 20 tons on each driving axle and 15 tons on the guiding axles.

Only one transformer is provided for the three motors, in order to keep down the weight (see Fig. 138).

The gearing is placed outside the frames, so as not to be hampered by restriction of space. This arrangement allows the space between the wheels to be kept free for the motor as well as permitting a greater width of gear than is obtainable with the designs employed heretofore, as the whole of the space between the driving wheels and the loading gauge becomes available. The centre of the gear wheel is somewhat higher than that of the driving wheel, in order to obtain a satisfactory gear ratio. The gear wheel is connected to the driving wheel by means of the special coupling device, which is elastic in all directions, so that a certain displacement of the driving axle as regards the locomotive frame can take place freely in a vertical and a lateral direction, it even being possible for the wheels to adapt themselves to curves if necessary.

The construction of the coupling device between the gear wheel and driving wheel is extremely simple (see Fig. 139). Relative movements of the gear wheel and driving wheel can take place without restraint. The consequent freedom with which the coupling can adjust itself when the spring-borne portion of the locomotive rises and falls with regard to the frame is especially noteworthy. The gear wheel turns loose on a pin which has a conical end let into the gear-casing. The overhung mounting of this gear wheel is unusual. On account of the freedom of movement, driving wheels mounted on the same frame having tyres of different thickness can be allowed to run. It follows that when unequal wear to the tyres of the driving wheels occurs, it is no longer necessary for the locomotive to be lifted in order to remove all the sets of wheels for returning, as with a side-rod drive. The easy access to the coupling device and movable flaps on the gear casing offers many advantages. For instance, if a breakdown due to motor or gearing defects should occur between stations, no great delay will be experienced with these locomotives, as the coupling device enables the driving wheels to be easily and rapidly disconnected from the

gearing. An entirely automatic method of forced lubrication is used for the gears.

Each motor, one per driving axle, has a one-hour rating of 700 h.p. at 500 r.p.m. There is, however, ample space for motors of still higher outputs to be easily fitted. The total one-hour rating of these locomotives therefore amounts to 2100 h.p. A train weighing 472 tons can be hauled by one locomotive of this class at 40 m.p.h. up a 1 in 100 gradient, or at 55 m.p.h. up a 1 in 500 gradient. During trials, one of these locomotives started and hauled a train of 120 axles weighing 711 tons up a 1 in 100 gradient without the slightest difficulty, tractive efforts up to 26,432 lb. having been developed. In Europe, where axle loads of 20 tons are rarely exceeded, higher outputs per axle than those of these locomotives are not required. In America, however, where loads of as much as 30 tons per axle are allowed on certain railways, motors rated at 1000 h.p. per axle could be fully utilised with the individual drive. The motors are of the usual neutralised series type.

This locomotive has been described as an example of the possibilities of individual axle drive with single-phase motors, since this system of drive is strongly urged as an outstanding advantage of the direct-current system. The advantages claimed by Brown-Boveri & Co. for the individual axle drive described, are briefly stated as follows :—

(1) The individual axle drive is without doubt the class of drive which is best suited to the peculiarities of the electric motor

(2) The stresses on the bearings are diminished by doing away with the alternating thrust of the coupling rods. Special devices for taking up the play in the bearings and coupling rods are no longer necessary.

(3) The tendency to vibrate no longer exists.

(4) The gearing can be liberally dimensioned without prejudice to the motors.

(5) The distribution of the spring-borne weights is such that their moment of inertia with regard to the longitudinal axis of the locomotive is exceptionally great ; this ensures steady and smooth running, both on straight track and when rounding curves.

(6) The frames are light, but extremely strong, no openings having to be provided for the motor and jackshaft bearings as with a side-rod drive.

(7) The wear of the flanges is extremely small, as each pair of driving wheels can have side play, and, if required, a certain radial adjustment. It follows that the wear and tear of the track is reduced.

(8) Driving wheels belonging to the same group and having tyres of different thickness can be allowed to run without inconvenience.

(9) Each motor can be quickly uncoupled without difficulty when between stations.

(10) The completely automatic forced lubrication of the running parts of the drive, together with the continuous filtering of the oil, enables a great deal of time and labour to be saved.

Type III. Description of Single-phase Locomotive Characterised by the Use of a Single 3000 h.p. Motor.—As a typical example of a locomotive with a single high-power motor (see Fig. 140), we may take one of the seven 2-C-2 (4-6-4) single-phase express locomotives designed and built by the Bergmann Elektricitäts Werke A.G. (Berlin) in conjunction with the Berliner Maschinenbau A.G., for use on lines between Magdeburg, Halle, and Leipzig. These are designed for the haulage of heavy trains, up to 660 tons coupled weight at express speeds. In order that the weight and cost of the locomotive may be kept a minimum, a single motor is employed, this being mounted high and driving the three coupled axles through a system of rods with two crankshafts. This type of construction was also used in the twelve heavy passenger locomotives supplied by the same firm to the Görlitz-Hirschberg-Konigszelt (Silesia) mountain railway, and the exceptionally good results there obtained during a

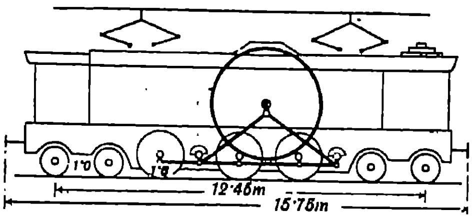


FIG. 140.—Diagram of single-phase locomotive characterised by the use of a single 3000 h.p. motor.

prolonged period, on heavy gradients and sharp curves, led to the adoption of the same type of locomotive in the Halle division.

The locomotive is normally driven from the cab at the front, but can be driven from the other cab if that end be leading. Immediately behind the front cab is the transformer room; then comes the motor compressor, and above it the oil switch. The main motor (Fig. 141) is centred between the second and third coupled axles and a hood is formed on the roof to accommodate the top of the stator frame. Behind the motor room is the second cab, and at the rear of the locomotive a boiler which provides steam for heating the train. Ample provision for ingress of air is made in the form of drop windows, as shown. There are also louvres which can be closed by flaps in bad weather. A separate air chamber is partitioned off for the discharge of hot air from the machine room.

The arrangement has the advantage that the electrical equipment consists of a very few large components, and, in particular, the motor is situated high in the locomotive, is entirely open, and is easily accessible from all sides.

Inspection and maintenance are thereby facilitated. Workshop operations are also made easy, the erection and dismantling of the motor being simplified by the horizontal division of the stator frame into two parts. The heaviest part of the motor, the armature and shaft, has only about the same weight as the transformer (Fig. 133) with its built-on control gear, so that no specially powerful crane or lifting tackle is needed. The principal dimensions and weights are as follows :—

Gauge	1,435	mm.	(4 ft. 8½ ins.).
Driving wheels, diameter	1,600	,,	(5 ft. 3 ins.).
Leading ,, ,,	1,000	,,	(3 ft. 3⅜ ins.).
Crank circle ,,	600	,,	(1 ft. 11⅝ ins.).
Total wheelbase	12,450	,,	(40 ft. 10 ins.).
Rigid ,,	4,650	,,	(15 ft. 3 ins.).
Distance between bogie centres	10,650	,,	(34 ft. 11¼ ins.).
Total length over buffers	15,750	,,	(51 ft. 8 ins.).
Overall width	3,100	,,	(10 ft. 2 ins.).
Height of roof	3,850	,,	(12 ft. 7½ ins.).

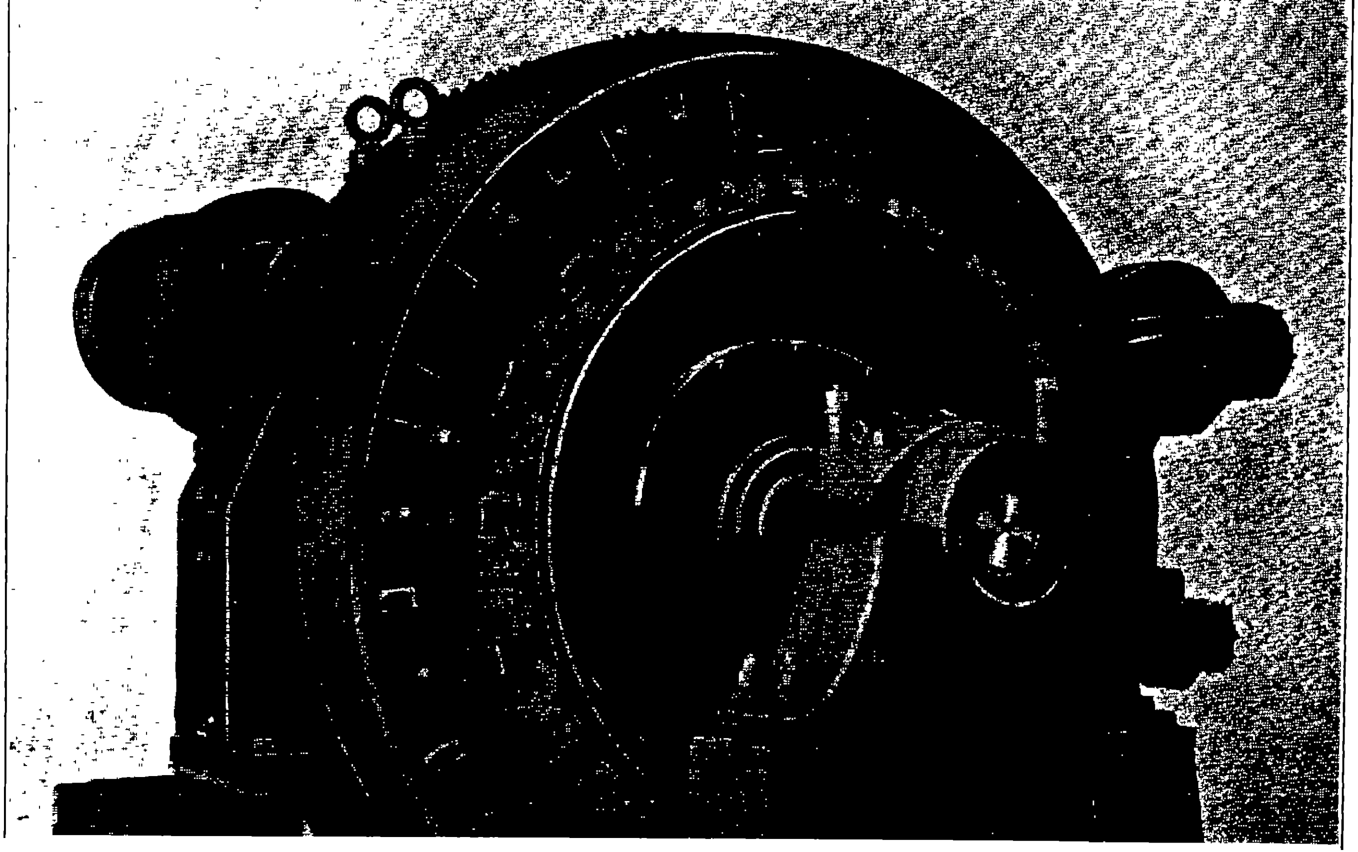


FIG. 141.—Single-phase motor on express locomotive, German State Railways: 2960 h.p. at one-hour rating; 250-380 r.p.m.; 350 volts. Locomotive attains a maximum speed of 68½ miles per hour with a load of 660 tons. Trolley voltage is 15,000. Cranks and side rods are used. Auxiliary ventilating fans on motor can be seen above. Control is by brush position variation, both as to direction and output.

[*To face page* 224.

Weights.

Electrical equipment with oil-immersed transformer	42,000 kg. (41⅓ tons) or 14 kg. per metric h.p. or 31·2 lb. per h.p.
Electrical equipment with dry-type transformer	38,000 kg. (37⅓ tons), or 12·7 kg. per metric h.p., or 28·3 lb. per h.p.
Mechanical equipment, including 3·45 tons for heating boiler, empty, and an equal weight for fuel and water	76,500 kg. (75¼ tons).

Total Service Weight.

With oil-immersed transformer, heating boiler and stoves	118,500 kg. (116½ tons), or 39·5 kg. per metric h.p., or 88·1 lb. per h.p.
With dry-type transformer and without boiler or stoves	107·500 kg. (106 tons), or 36 kg. per metric h.p., or 80·3 lb. per h.p.
Adhesive weight	56,000 kg. (55 tons).
Load per driving axle	18,600 ,, (18·4 tons).
Load per leading axle—	
With oil transformer	15,600 ,, (15·4 tons).
With dry transformer	12,900 ,, (12·7 tons).

A distinctive and valuable feature of these locomotives, not obtained with other methods of driving, is that the whole width between the frame plates is available for the motor armature. By the use of a special armature winding the available width is fully utilised, and a high motor output is obtained from a rotor of relatively small diameter.

The stator also has special features. Whereas motors for this class of service have usually two stator windings—a field winding and a compensating winding—displaced half a pole pitch—with regard to each other, the motor of this locomotive has only a single winding on the stator. The amount of copper required in the machine is thus reduced, manufacture is simplified, and there are only two connections, each for half the motor current between the two parts of the stator. Finally, the overall height, and therefore the weight of the stator, is reduced. By these means it has been possible to obtain a motor output of 3000 h.p. (one-hour rating) with a stator plate diameter of only 2800 mm. (9 ft. 2¼ ins.), while the weight of the motor, excluding the shaft, is only 18,700 kg. (41, 140 lb.),

corresponding to the unusually low value of 6·23 kg. (13·7 lb.) per horse-power.

It may be added that the one-hour rating of the similar motors used in the Görlitz-Konigszelt locomotives is based upon a current of 9000 amperes at 290 volts, and a speed of 250 r.p.m., while the continuous rating is based upon 7300 amperes at 270 volts, and speeds from 250 to 380 r.p.m. The weight of the upper half of the stator is 7920 lb., that of the lower half 8360 lb., that of the armature (excluding shaft) 21,560 lb., and that of the brush yoke, 3300 lb.

The principal power data are :—

Motor Output—	
One-hour rating	3000 h.p.
Continuous	2250 ,,
Tractive Effort at Wheel Rim—	
One-hour rating	10,000 kg. at 75 km. per hour.
,, ,, ...	22,000 lb. at 46$\frac{1}{2}$ m.p.h.
Continuous rating . . .	7500 kg. at 75 km. per hour.
,, ,, ...	16,500 lb. at 46$\frac{1}{2}$ m.p.h.
,, ,, ...	5600 kg. at 100 km. per hour.
,, ,, ...	12,322 lb. at 62 m.p.h.
Maximum speed	110 km. per hour (68$\frac{1}{2}$ m.p.h.).
Guaranteed starting effort at drawbar	13,000 kg. (28,600 lb.).
Maximum tractive effort . .	16,500 kg. (36,300 lb.).

A further advantage of the simplified stator winding is that the controller, which would be large and costly for the heavy currents concerned, is eliminated. Reversal is effected by brush-shifting, and this means is also employed to keep the motor-power (which would otherwise decrease according to the ordinary series motor characteristic) almost up to its full value at the higher speeds. This result is obtained without the use of other equipment such as switches, supplementary steps on the transformer, and so on.

Transformers and Other Electrical Equipment.—As regards the transformer oil insulation was used on the first five of the locomotives to be delivered, but on the other two the transformers are not oil-immersed. This difference is due to the railway authorities themselves. In certain cases somewhat unsatisfactory results had been obtained with dry transformers, and as a precautionary measure oil insulation was therefore

employed for the first five locomotives. In the meantime, however, the dry transformers on the previously mentioned passenger locomotives for the Silesian mountain railway had given such good results that the authorities reverted to this practice for the last two locomotives in the seven for the Halle line.

The dry-type transformer is about 25 per cent. lighter than the equivalent oil-immersed transformer; also, it is of higher efficiency, simpler to erect, costs very little to maintain, and requires no attendance or supervision in service. The impregnation of the coils protects them against dust, moisture, and other detrimental agencies.

In view of the high motor current, the contactors, which are built right on to the transformer, are operated by compressed air. The transformer is rated 15,000/350 volts, 1650 k.V.A. continuous output. The weight is 18,700 lb., or 11·3 lb. per k.V.A.

Where oil-immersed transformers are used, the oil is pumped through a system of pipes in lateral casings at the sides of the transformer, and cooled by a blower which draws air from the machine room and delivers it to the open through casings. Current is collected from the overhead line by bows mounted on pantograph frames. The high-voltage connections run along the roof, and the main oil switch is placed partly in the roof, over the motor compressor.

The electrical equipment thus comprises four main components, viz. the current-collecting gear, the oil switch, the transformer and its switch gear, and the motor. To these are added the usual auxiliary equipment, such as the motor compressor, providing air for braking, the cooling blowers, lighting and heating equipment, etc.

The motor compressor, rated at 90 cubic metres (3180 cub. ft.) per hour at 8 kg. per square centimetre (117 lb. per square inch) is placed between the transformer and the motor. The drive from the motor shaft to the driving wheels is one of the most interesting features of these locomotives. It is effected by two pairs of driving rods, which are displaced 90 degrees with regard to each other, and connect the motor shaft to the two crankshafts. Thence, the drive is by horizontal connecting

rods to the three driving axles. There is thus on each side the locomotive a system of rods in the form of a closed rig angled triangle without dead centres. The behaviour of t drive in service is particularly favourable. Transverse oscil tion is completely avoided, even if the bearing play amou to several millimetres, and the locomotives can therefore rema in service for months at a time without adjustment.

Originally, in accordance with the requirements of the ra way authorities, damping springs were provided between t armature spider and the main shaft, as is now common pract where mixed gear and rod-drive is employed.

Experience in service has shown, however, that any su device is quite unnecessary so far as these large rod-drivi motors are concerned. The damping springs have already be removed from some of the locomotives, and will be taken o of the others as opportunity arises. In new constructions, bu without the damping springs, the armature spider would modified accordingly, and the weight of the electrical equ ment thus further reduced. This constitutes a considera advantage of the pure rod-drive compared with the mixed g and rod drive, for the latter must embody a damping devi The motor and crankshafts run in ball bearings, those on t motor shaft being provided with oil-circulation, while the cra shaft bearings are lubricated by a Bosch pump. The lub cating devices are actuated by links and levers from the coup axles.

The equipment of both cabs is substantially the same, a includes a driver's board, the board on each cab being on right hand when the cab is leading. The maximum permissi current when starting is 9000 amperes on level track, and 12,0 amperes on a gradient; while the current limit for advanc the controller is 9000 amperes or, exceptionally, 10,000 ampe The maximum current for one-hour rating is 9000 ampe and for continuous rating 7000 amperes.

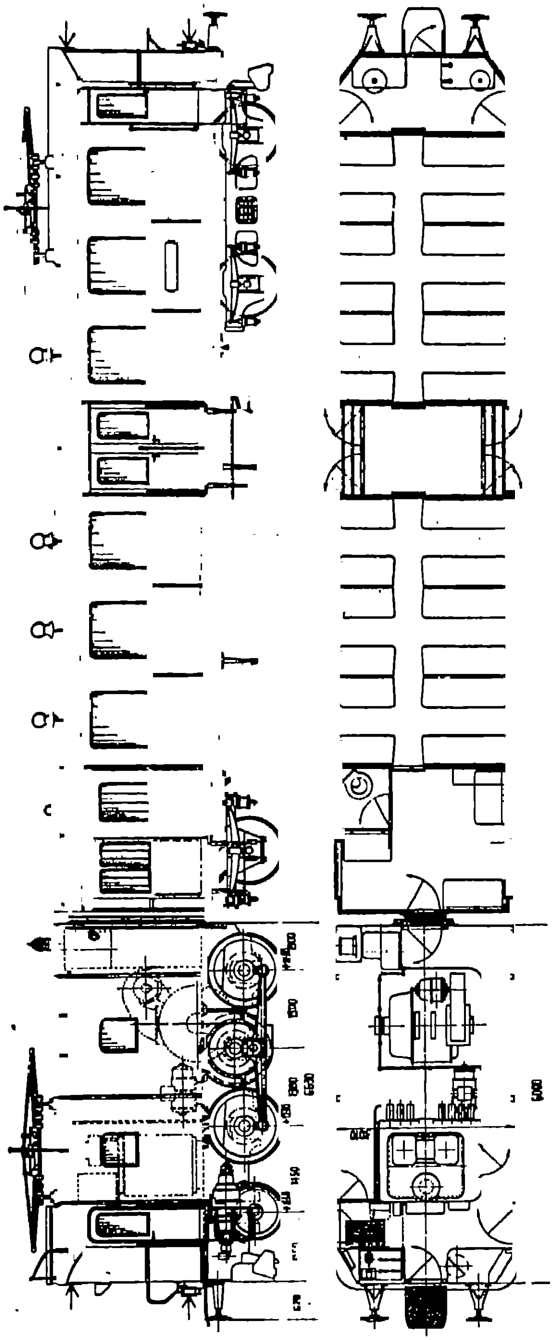
Type IV. Motor Coaches on the Loetschberg Railway.—T Loetschberg Railway Company has recently put into service its Bern section two motor coaches which should be of spec interest, as they differ from standard design in various respe

Each motor coach has to develop an hourly output of ab

500 h.p. at the wheel rim at a speed of 21·7 m.p.h. It was specially stipulated that the motors of the new coaches were to be, as far as possible, similar to those already in the company's stores. In view of this it was decided to adopt motors of the same type as those supplied by the Oerlikon Company for seven locomotives, Nos. 301 to 307, of the "Bernese Decree Railways," as these complied with the above condition, and had given entire satisfaction during the five years they had been in operation: the motors were built for a 518 h.p. one-hour rating at 21·7 m.p.h. Fig. 142 gives the general dimensions of the motor coaches in question. As can be seen, they are somewhat similar in design to the motor coaches supplied in 1921 to the Burgdorf-Thun Railway.

The electrical equipment is grouped on a three axle bogie fitted with two driving axles and one guiding axle; this frame is coupled to the main frame carrying the passenger and luggage compartments. The motor coach thus consists of a small locomotive and a passenger coach. In order to permit of the operation of the motor coach in either direction, the passenger coach itself is also fitted with a driver's cab, and, furthermore, both the passenger coach and locomotive portions are fitted with pantograph collectors.

The locomotive portion contains, as already stated, all the electrical equipment. The supply is 15,000 volts, 16⅔ cycles, single-phase. The current is led from the collector gear through isolating switches to the main circuit breaker, which is built for outdoor mounting; this circuit breaker is arranged for electro-pneumatic closing and for electrical release. The second pole of the circuit breaker is connected to the high-tension terminal of the transformer; the latter is of the oil-immersed self-cooled type. In order to improve the cooling the transformer is enclosed in a second casing into which air is drawn from the roof; this air passes over the transformer and escapes into the motor room. The low-tension winding has eleven tappings, which are connected to the motor as required for the various speeds. The highest pressure applied to the motor is about 500 volts. The connection between the transformer tappings and the motor is ensured by means of twelve contactors. These are controlled electro-pneumatically, and



Elevation and plan of motor coaches No. 784 and 785 of the Loetschberg Railway.

FIG. 142.

are interlocked to prevent short-circuits; they are arranged in the motor room. The passage from one notch to the next is made in the usual way by means of a preventive coil. The motor has ten poles and a continuous output of 425 h.p. at 24·2 m.p.h. On the motor coaches of the Burgdorf-Thun Railway the torque is transmitted to the two driving axles by means of the Oerlikon geared individual drive; in the present case, however, the two driving axles are coupled together by means of a triangular system of rods, and connected to the motor through a jack-shaft. In this way it has been possible to use not only similar motors, but also the same gearing. The reverser, which has two positions for forward and reverse operation respectively, is mounted on the motor frame together with a fan set; the latter draws the air from the motor room and drives it through the motor and out through openings provided below. The direct current at 36 volts for the control circuits and lighting is supplied by a 1 kw. motor generator set and a battery of accumulators. The heating current for the different compartments is derived from a tapping on the transformer giving 1000 volts through an electro-pneumatically operated circuit breaker. Other auxiliaries are supplied from a 220 volt tapping.

The motor coaches are built for multiple control and automatic acceleration. The following table contains a few further particulars of these coaches. The mechanical part of the driving bogie was supplied by the Swiss Locomotive and Machine Works, while the coaches themselves were built by the Swiss Industrial Company of Neuhausen:—

Gauge	4 ft. 8·5 ins.
Smallest radius of curves	590/374 ft.
Steepest gradient	1 in 40.
Maximum permissible load per driving axle	12·75 tons.
Nature of train	Passenger train.
Normal speed	21·7 m.p.h.
Maximum speed	40 m.p.h.
Output at wheel rim at 21·7 m.p.h. (one hour rating)	518 h.p.
Output at wheel rim at 24·2 m.p.h. (continuous)	425 h.p.
Tractive effort at wheel rim at 21·7 m.p.h. (one hour rating)	8800 lb.

Tractive effort at wheel rim at 24·2 m.p.h. (continuous)	6460 lb.
Maximum tractive effort	13,200 lb.
Diameter of driving wheels (new tyres)	4 ft. 4 ins.
Gear ratio	1 to 3·78.
Fixed wheel base	8 ft. 6·3 ins.
Length over buffers	71 ft. 8·2 ins.
Total weight	60·1 tons.
Weight of the electrical equipment	15·4 ,,
Weight of the mechanical part (driving bogie and coach)	44·7 ,,
Adhesive weight	25·5 ,,
Current system single-phase	——
Pressure, 15,000 volts	+ 5 per cent.
,, ,,	− 15 ,,
Frequency, $16\frac{2}{3}$ cycles	$\pm \frac{1}{2}$,,
Seating Accommodation—	
Smoking compartment	30
Non-smoking ,,	30
Luggage ,,	5
Standing accommodation in luggage compartment	15

CHAPTER VIII.

THE APPLICATION OF COMMUTATOR MACHINES TO THE DRIVES OF ROLLING MILLS.

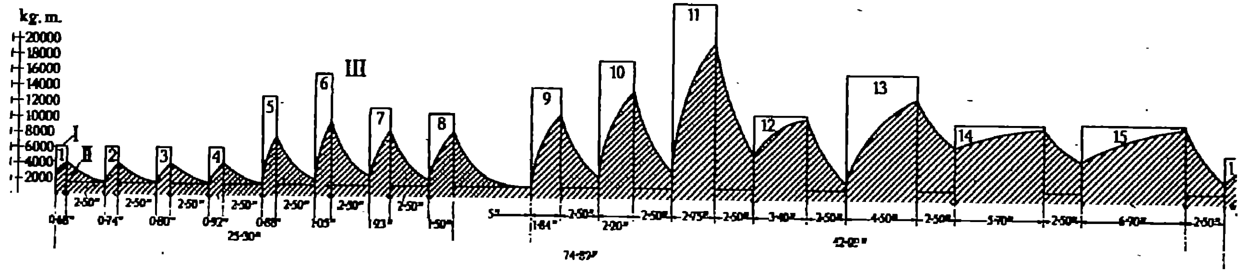
It is only comparatively recently that the first attempts were made to drive rolling mills electrically. The reason of this is to be found in the arduous duties such drives have to fulfil, since the power consumption fluctuates continually from no-load to extremely high outputs, as may be seen in Figs. 143 to 146.

These peaks can be so considerable that they attain values of ten times the normal output of the driving motor.

This application has been chosen consequently as typical of the advantages of the larger commutator machines ; the more so as it introduces not only the three-phase commutator motor as a unit by itself, but also various combinations of induction motors and commutator machines either in cascade on the same shaft or running as separate auxiliary units (Kramer and Scherbius systems).

Apart from the question of power-factor compensation, which is the most important application for the smaller polyphase commutator machines, the question of rolling-mill drives is perhaps the most important application of the larger types, and one that is attaining increasing popularity. The systems of drive described, though primarily designed for rolling-mill work, are obviously susceptible to further development and many other applications, some of which will be dealt with in a subsequent chapter.

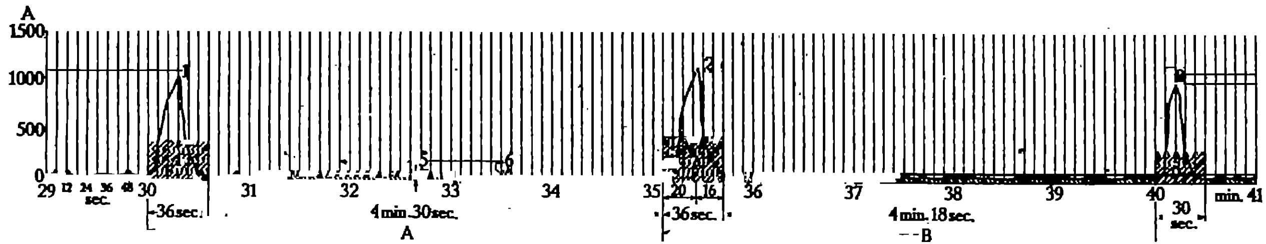
Rolling-Mill Motor Characteristics.—A rolling-mill motor must possess certain definite characteristics. If these be clearly enunciated, it is a comparatively simple matter to study a suitable drive. We will only concern ourselves here with the drive of non-reversible rolls provided with flywheels.



Power and torque of a three-high mill for rolling ingots of about 236 × 200 mm. cross section, 1100 mm. long, weighing about 510 kg, into joists of 200 × 60 × 6 mm, and about 15'000 mm. long.

I. Necessary rolling torque in kg.m. II. Output of rolling-mill motor in kW. III. Peak outputs taken by the flywheel masses.

FIG. 143.



Current-demand diagram when rolling a hollow ingot of 160 mm. external diameter, 25 mm. thick, in a Mannesmann piercer.

Duration of pass A: 5 min. 6 sec. Duration of pass B: 4 min. 54 sec.

1 = 820 H. P., 2 = 920 H. P., 3 = 750 H. P., 4 = 320 H. P., 5 = 40 H. P., 6 = 75 H. P., 7 = 370 H. P., 8 = 250 H. P.

FIG. 144.

The requirements of rolling-mill operation are the following :—

(1) An appreciable drop in speed between no-load and full-load.

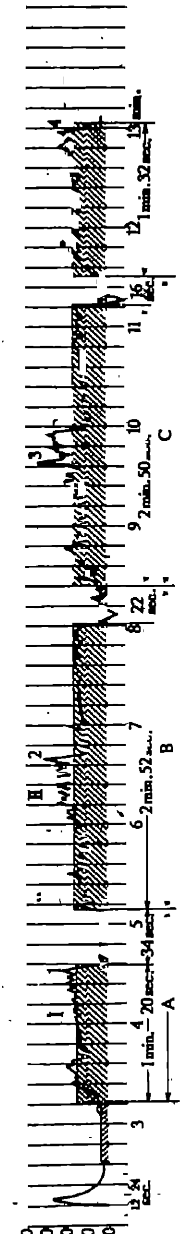
(2) The possibility of adjusting the amount of this drop.

(3) The possibility of obtaining a range of no-load speeds without excessive loss, each of which has itself an adjustable speed drop from no-load to full-load.

The reasons for the last two requirements are to be found in the varying operating conditions according to the work on hand, and are purely metallurgical. The first requirement, on the other hand, is mechanical, and the point of the speed drop from no-load to full-load is to enable the flywheel to act effectively. Finally, there is a subsidiary condition in that the motor must be able to come up to speed again very rapidly after a peak.

The Effective Use of Flywheels.—Before proceeding any further with the subject, the action of the flywheel should be clearly understood. The conditions of flywheel operation can best be studied from a numerical example.

Let us consider the case of a mill, the diameter of the rolls being 550 mm., driven by a 550 h.p. motor at 120 r.p.m., provided with



Current-demand diagram when rolling a tube of 97 mm. external diameter in a Pilger mill.
I. Simple rolling diagram. II. Double rolling diagram.
Duration of pass A: 1 min. 54 sec. Duration of pass B: 3 min. 14 sec. Duration of pass C: 3 min. 6 sec.
1 = 360 H.P., 2 = 510 H.P., 3 = 550 H.P., 4 = 390 H.P.

FIG. 145.

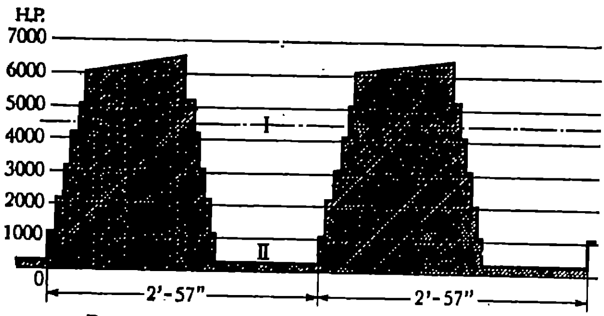
a 40-ton (metric) flywheel with a diameter of gyration equal to 5 metres 50.

Let us assume that during the roll the motor slows down 10 per cent. During this drop in speed the flywheel will liberate a certain amount of energy. The expression for this energy is

$$\frac{1}{2} M(V_1^2 - V_2^2) = \frac{1}{2} \frac{40{,}000}{9 \cdot 81} (34 \cdot 4^2 - 31 \cdot 1^2) = 460{,}000 \text{ Kg.M.}$$

Assuming the duration of pass to be 3 seconds, the power supplied by the flywheel will be

$$\frac{460{,}000}{3 \times 75} = 2{,}050 \text{ h.p.}$$



— Power in H. P. taken by a Morgan continuous mill, having rolls of 457 mm. average diameter, for rolling 4530 kg. ingots into strips of 305 × 8 mm. cross section and about 240 m. long, the output amounting to 100 tons per hour.

I. Root-mean-value. II. Friction losses.

FIG. 146.

If the duration of pass was 10 seconds, the power supplied would amount to 613 h.p., and only 102 h.p. if the pass lasted 60 seconds.

The example shows the importance of the work done by the flywheel, which, for a given flywheel depends only on the initial speed and the percentage of speed drop.

When the pass is of fairly long duration the flywheel loses much of its efficiency, and may, in fact, become disadvantageous if the energy it absorbs is not compensated by the energy it supplies.

In other words, the flywheel will be the more effective the more rapid and the more frequent the load variations. If the

peaks are of long duration it is more advantageous to use a more powerful motor and suppress the flywheel altogether. On the other hand, it must be remembered that sufficient time should elapse between passes for the flywheel to be brought up to normal speed again.

One of the conditions, therefore, which the motor characteristic will have to fulfil is that the speed should rapidly rise again as soon as a peak has occurred.

The speed drop in a mill drive which enables the flywheel to become effective is known as the slip. It should be noted that the energy liberated from the flywheel is not, however, proportional to the slip, as can be seen from the following table :—

Slip per cent.	Energy as a percentage of total flywheel energy.
1	2
3	9·6
10	19
20	36
30	51
50	75
100	100

This is also shown by the accompanying curve (Fig. 147).

Moreover, if we consider a flywheel operating at different speeds between 100 and 200 r.p.m. for a given per cent. slip, the liberated energy will be greater at 200 r.p.m. than at 100 r.p.m. In choosing values for the weight of a flywheel, it would seem advantageous at first sight to assume a fairly high value for the slip. In practice, however, the slip is limited to some 15 per cent. for the following reasons :—

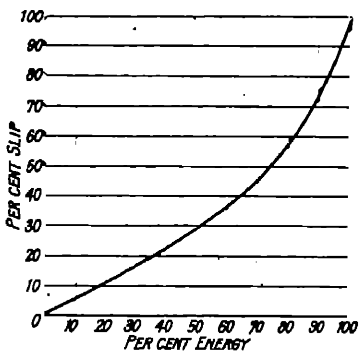


FIG. 147.—Curve showing variation of energy, as a percentage of total flywheel energy, with slip.

(1) Any considerable drop in speed must affect adversely the regular operation of the rolling mill, and consequently the production will suffer.

(2) Considerable slips can only be obtained with more expensive motors, or else at the expense of efficiency.

As regards the peripheral speed, the following values are commonly found in practice. For cast-iron flywheels of the rim and spoke type, 40 metres per second (120 ft. approximately). For steel wheels, rim and spoke type, 90 to 95 metres per second (270 to 285 ft. approximately). For steel wheels, disc type, 115 to 120 metres per second (345 to 360 ft. approximately).

It will be seen that, for any given operating conditions, the steel type will be far lighter than the cast-iron type, since the kinetic energy is proportional to the square of the speed.

Unfortunately it is not always possible to utilise the highest peripheral speed, because a certain definite relation exists between the weight and the speed.

Let us consider a motor operating under greatly varying loads and compare the heating of such a motor from Joule effects with that of a motor doing the same amount of work, but under constant load.

Let us take a concrete example.

In the first case the conditions are as follows: During one second, 1000 h.p. followed by three seconds on no-load. The average load will be 250 h.p.

In the second case the motor will be running under a constant load of 250 h.p.

Over a certain period the work done by both motors will be identical, but it will be easy to see that the heat developed by Joule effect will be very different in both cases.

This heating effect is expressed by the formula RI^2t where R is the resistance in ohms, I the current in amperes,[2] t the duration in seconds. In calories, the quantity of heat produced is expressed by

$$\frac{RI^2t}{4170}.$$

Since the motors are identical and working through the same period, the heating will depend on the value of I.

The 1000 h.p. output corresponds to a current approxi-

mately four times greater than that for 250 h.p. The heat produced will be therefore sixteen times greater for 1000 h.p. than for 250 h.p. But as this output takes place only during one-quarter of the time, the heating will actually be four times as great for the variable load as it is for the constant load. The *effective* power of a motor is thus defined as the constant power which it is capable of giving with the same heating as for a variable load.

Since motor outputs are limited by heating considerations, the value of some regulating device, such as a flywheel, will be readily appreciated.

As regards efficiency under variable load, it will, of course, be lower than would be the case for a constant load. However, in rolling-mill motors, the heating effect is usually only about 1 per cent. to 2 per cent. of the motor rating, and can consequently be considerably increased without affecting the efficiency to any great extent.

Before considering the application of commutator machines, a brief examination of the possibilities of direct-current and three-phase induction motors is necessary for a clear understanding of the problem.

Series wound direct-current motors are not applicable on account of the excessive speeding up on no-load.

Shunt wound direct-current motors are not very suitable either. Where the mill is provided with a flywheel there is not sufficient difference between speeds at full-load and no-load to allow it to act effectively, and on peak loads the flywheel will not be able to handle the excess torque, while the motor will draw an exaggerated amount of current from the mains. In the case of reversible rolling mills such a motor is applicable with independent excitation.

Compound wound direct-current motors are frequently used for mill drives. If we look at the characteristic curve of a compound motor (Fig. 148), it is at once apparent that there is a considerable drop in speed between no-load and full-load, and this can be so adjusted as to effectively utilise the flywheel. The drop in speed will not, in actual fact, be given by AB, but by CD, as the power necessary to drive the mill between passes must be taken into account.

The compound wound series motor has the following advantages :—

Simplicity and robustness ; appreciable drop in speed between full-load and no-load ; speed regulation may be easily obtained by weakening or strengthening the field.

There are, however, some disadvantages which may be overcome, but not without some trouble and complication. Fig. 148 shows both torque and speed as functions of the current. From these the speed torque curve can be easily deduced (Fig. 149).

Now, it will at once be seen from this curve that when the speed drops the torque increases, but the motor will only give normal torque for a perfectly definite value of the speed. Since

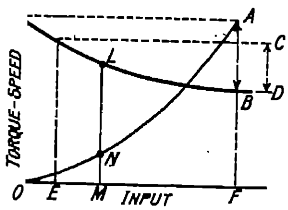


FIG. 148.—Characteristic curves of compound wound direct-current motor for rolling-mill drives.

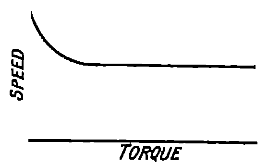


FIG. 149.—Speed-torque curve for compound wound diroct-current motor.

the motor speed is varying continually, the torque will also vary. If the motor should run at a speed slightly below its speed on normal load, the torque increases rapidly, and the input may rise dangerously. Such a motor, therefore, will only deliver its normal torque intermittently, since the normal speed is only intermittently attained, and the average power will consequently be lower than might be obtained with a constant load.

THREE-PHASE INDUCTION MOTORS FOR USE ON ROLLING-MILLS.

Induction Motor Used Alone.—The characteristic is similar to that of a shunt wound direct-current motor, and the difference in speed between no-load and full-load is only of the order of 2 per cent. for fairly large motors, and in order that such a

motor may be properly utilised certain modifications become necessary.

(*a*) **Use of a Constant Resistance in the Rotor Circuit.**—This resistance will, of course, increase the slip, and therefore the difference between speeds at no-load and full-load. The motor characteristic will resemble that shown in Fig. 150, but there are a number of disadvantages. The torque will vary considerably; when an overload occurs the motor will only effectively help the flywheel if the latter is already considerably slowed down. After such an overload the motor will take a long time to come up to speed.

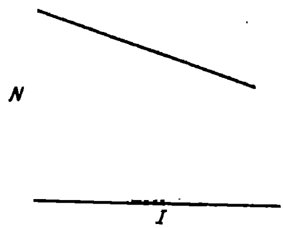


FIG. 150.—Characteristic curve of three-phase induction motor with resistance in rotor circuit for increasing the slip.

Moreover, due to the presence of a permanent resistance in the motor circuit, both the efficiency and the power factor will be bad. On the other hand, of course, speed regulation can be easily obtained by varying the values of the inserted resistance. When all the factors are considered, it will be seen that the method is not a commendable one.

(*b*) **Automatic Insertion of a Resistance in the Rotor Circuit as soon as the Current Rises Past a Certain Given Value.**—This can be easily brought about by means of a suitably designed system of relays and contactors.

But precautions must be taken in order to avoid the occurrence of a periodic phenomenon. As soon as the resistance is put into circuit the main current falls off, and the resistance is automatically cut out again, when the current rises once more. In order to avoid this effect, things have to be so arranged that the resistance is only taken out of circuit when the current has fallen considerably below its primitive value.

But this has the disadvantage that the motor is reduced in power during the time the resistance remains in circuit.

(*c*) **Automatic Insertion of a Resistance in the Rotor Circuit that will Vary as the Main Current Varies.**—This is easily done by the use of a liquid rheostat, and is very fairly satisfactory. There are a number of defects common to all the above methods.

The speed at no-load cannot be varied; power factor and efficiency are necessarily low. The latter defect, low-power factor and low efficiency, equally applies to the use of regulators such as the Thury type, for instance, and it may be concluded that the induction motor by itself is not a satisfactory motor for the drive of rolling-mills.

Direct-current motors, of course, entail converting apparatus which is both costly and bulky, and reduces the overall efficiency of the installation. Although a plurality of machines is very often used in cases where commutator machines are applied, the number of machines is smaller than in the case, say, of a Ward-Leonard set, and the efficiency, and, above all, the power factor, are very much more satisfactory.

The next step in the design of rolling-mill drives consisted in the adoption of cascaded induction motors, and it is necessary to say a few words about this system before concluding these preliminary remarks.

The Use of Cascaded Induction Motors.—The principle of this method is well known to all, and certainly affords better operating conditions than may be obtained with a single unit. It will, of course, be most advantageous where two or more definite speeds are required, a condition often found in rolling mills.

This method of regulation consists in having a second motor on the same shaft as the main motor, and connected in series with the rotor of the latter. Starting and speed regulation are carried out by resistances in the circuit of the second motor. The speed at which the two motors tend to run corresponds to the frequency of the current supplied to the main motor, and to the total number of poles of the two motors.

It is given by the following equation :—

$$n = \frac{60f}{p_1 + p_2} \text{ r.p.m.}$$

where f = frequency of the alternating current supplied.

p_1 = number of pairs of poles of the first motor.

p_2 = number of pairs of poles of the second motor.

With such a set three speeds are possible which correspond to p_1, p_2 and $p_1 + p_2$ pairs of poles respectively. Further, if

the main motor is provided with connections giving two different numbers of poles, the set has five different speeds.

Pole-changing connections and cascade connection have not been employed, however, to any great extent for rolling-mill drives, because they give a jerky regulation of the speed and only enable intermediate speeds to be reached by means of resistances.

Furthermore, the overload capacity is small, the mechanical efficiency poor, and the power factor unfavourable. On account of all these shortcomings, other methods of regulation have been developed and successfully applied to rolling-mill motors. They not only allow constant speed to be maintained independently of the load, but also speed regulation to be undertaken at no-load, as we shall presently see.

The foregoing remarks can be briefly summed up as follows :—

Direct-Current Motors.

Advantages.—

(1) By varying the value of the excitation, a whole range of speeds can be obtained varying within wide limits, and the loss in the rheostats is reasonably small.

(2) The power is approximately constant at all speeds, and consequently the torque rises when the speed drops, which is a notable advantage where flywheels are used.

(3) The slip or drop in speed is economical as compared to that of an induction motor.

Disadvantages.—If direct current is generated and the power station is some distance away, transmission losses, or, if excessive copper is used, transmission costs, are high. If direct current is locally generated by conversion, the efficiency is low, the first cost high, the installation is bulky.

Induction Motors.

Advantages.—

(1) The first cost is low.

(2) The motor may be direct connected to an alternating-current supply

(3) The voltage used may be high.

(4) Maintenance costs are very low.

Disadvantages.—

(1) Speed regulation is impossible.

(2) Slip can only be obtained at the expense of considerable loss.

(3) The rheostat necessitates considerable quantities of water and some supervision.

(4) The power factor and the efficiency are low.

The Use of Commutator Machines.

The most simple manner of obtaining extended speed regulation with three-phase current is afforded by three-phase commutator motors which drive the rolling mill directly.

Starting and speed regulation are carried out without losses simply by displacing the movable brushes on the commutator. These motors have proved very satisfactory for rolling mills where load fluctuations are not too severe. Regulating contrivances have been perfected, however, which render practicable the use of three-phase induction motors in conjunction with commutator machines, and the two most commonly met with are :—

(1) A rotary converter in cascade with the main induction motor or Kramer system.

(2) A commutator machine in cascade with the main induction motor or Scherbius system.

The compound type of commutator motor, that is to say, a three-phase commutator motor coupled with an induction regulator, which is described in Chapter IV., is of course perfectly suited to rolling-mill conditions, and it is mainly under this form that it has been used. There are a number of these motors in use for rolling-mill drives on the Continent, one of which is shown in Fig. 151. This is a three-phase 400 to 450 h.p. motor, the speed varying from 350 to 450 r.p.m., and is installed in the Jeumont rolling mills.

But the most important systems used in conjunction with rolling mills are the Kramer and Scherbius systems, since these are suitable for heavier duties than the three-phase commutator motor as a unit by itself. The latter, particularly the compound type, is an ideal machine for the lighter mills, such

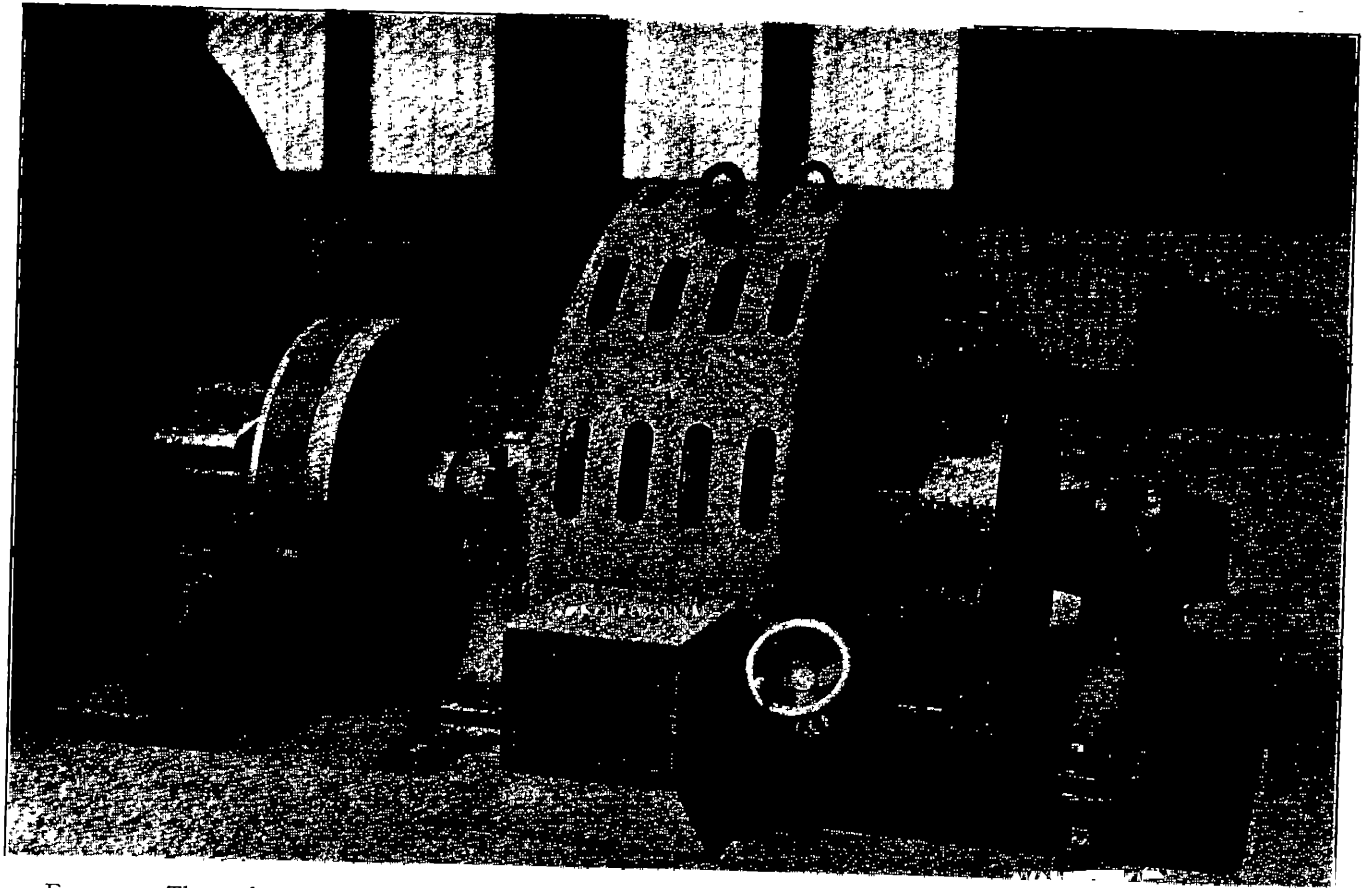


FIG. 151.—Three-phase 400-450 h.p. motor, 350-450 r.p.m., by the Forges et Ateliers de Constructions Electriques de Jeumont (Nord), installed in their own rolling mills.

[*To face page* 244.

as tyre and hoop mills, for instance, but, just as in the case of power-factor compensation, the commutator machine is most important when used in conjunction with an induction motor, so for very heavy duties, such as rolling mills, this combination is again of outstanding interest, and it is proposed to examine its possibilities in the present chapter.

The Kramer System.—The Kramer system involves the use of a rotary converter in cascade with the main motor. In this case, the slip energy which is lost as heat with resistance regu-

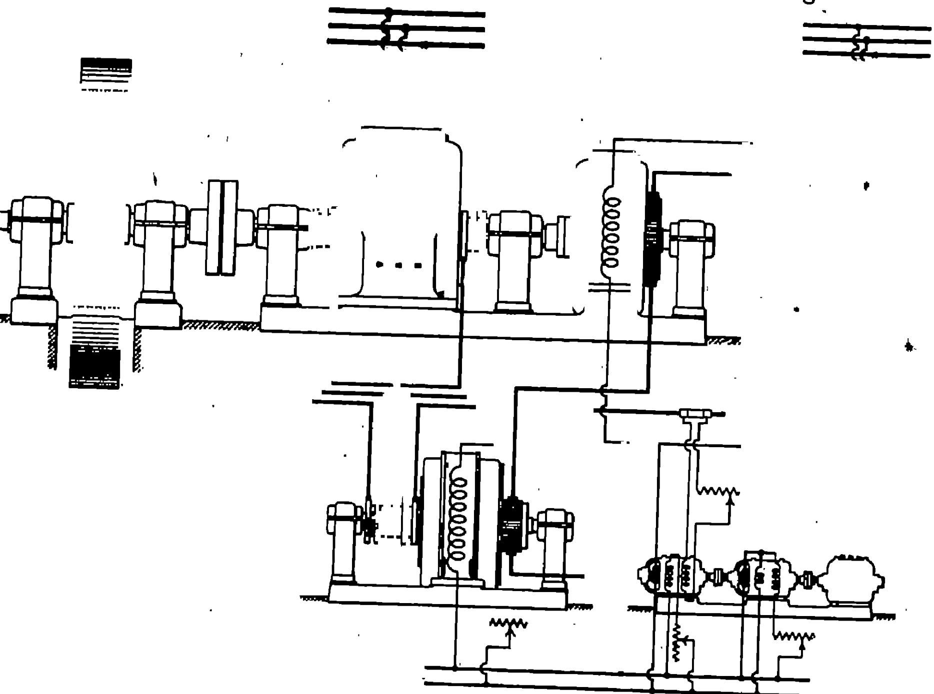


FIG. 152.—Kramer control, with flywheel and supplementary booster (Brown-Boveri).

lation is converted into direct current by a rotary converter, and is then supplied to a direct-current auxiliary motor (Fig. 152). The speed can be adjusted without losses by merely altering the shunt excitation of the auxiliary motor : an increase in this excitation leads to a higher pressure at the slip-rings of the main motor, and since the rotor pressure and speed are inversely proportional, the speed of the main motor falls. Consequently, once an adjustment has been carried out, the speed can be made to remain unchanged even at no-load.

By coupling the auxiliary motor directly to the shaft of the main motor, the slip energy is converted into mechanical output, whereas by making it drive an induction generator or alternator, the slip energy is returned to the distribution system. In the first case, constant power is ensured, and in the second, constant torque. The efficiency with the first arrangement is somewhat better; with the second, however, the auxiliary motor is cheaper if the speed of the main motor is low, as it can be constructed independently for the most suitable speed. Nevertheless, direct coupling of the auxiliary motor is generally preferred, as the efficiency is higher over the greater part of the speed range, and also one machine less is required. Furthermore, in the majority of cases, the direct drive offers no difficulties, due to the considerable number of types of direct-current machines available.

The two ends of the motor set are equally well adapted for driving the roll, and it is advantageous to use both if two different trains are driven simultaneously from the same motor. When the drive is on one side only, the shaft end is entirely covered by a sheet-iron cap, or done away with altogether. In the latter case, the outermost bearing can be smaller, or, with certain dispositions, entirely eliminated.

The rotary converter is ordinarily supplied with six-phase current, because this enables greater output to be obtained from machines of a given size than does three-phase current, and is, therefore, advantageous both with respect to the capital cost and to the efficiency: the load capacity of a given machine is, in fact, about 30 per cent. greater.

In the former case, however, the main motor has to have six slip-rings, which may, under certain circumstances, give rise to difficulties if Kramer regulation is added to an existing motor. In such cases, and when it is not feasible to make use of the Scherbius system, the larger, and consequently dearer, three-phase converter is unavoidable.

If a flywheel is provided as well as Kramer regulation, an additional speed-drop is necessary, so that the flywheel can come into action when there are sudden load peaks. This is brought about by having compound excitation for the auxiliary motor, which normally gives a speed-drop of about 10 per cent.

between no-load and full-load. By means of an adjustable shunt, the speed-drop can be altered. The compounding effect, however is less marked at low speeds than at high ones, on account of the increased saturation of the auxiliary motor—the load being assumed always the same. Hence, it is not possible to make the fullest use of the flywheel with extended speed regulation. Brown, Boveri & Co. introduced a method of indirect compounding, which consists of having in series, and differentially connected with the main field winding of the auxiliary motor, a small supplementary booster. The latter forms a separate set together with the main exciter of the auxiliary motor and a three-phase motor (Fig. 152). The booster has two field windings, one of which is connected across the same bus-bars as the primary excitation, and is provided with a field regulator, whereby the speed of the main set is carried at no-load. The other is traversed by the compounding current of the auxiliary motor in such a way that its effect is opposed to that of the first winding. When the load increases the counter pressure produced by the booster falls off, the shunt excitation of the motor consequently becomes greater, and the speed of the set lower. At low speeds, that is, with extended speed regulation of the main set, the pressure across the booster is low and its saturation reduced; the compounding current then develops its full effect, both on the pressure and on excitation of the booster, thereby ensuring an approximately constant speed-drop throughout the range of regulation.

Kramer regulation is particularly well adapted for high slip frequencies, that is, for extended speed regulation (as much as 50 per cent.). The synchronising torque of the rotary converter, however, becomes very small as the main motor approaches synchronism, so that sudden fluctuations of the load have a tendency to pull it out of step. To obviate this, the main motor must operate at speeds about 6 to 7 per cent. below synchronism. The range of regulation is thereby diminished by this amount, which can be made good, however, without impairing the overall efficiency by regulating with a resistance.

The Scherbius System.—In the Scherbius system the slip energy is no longer recuperated by the indirect method of converting it into direct current, but is supplied directly to a

three-phase commutator motor. As in the foregoing case, this motor can be mounted either on the same shaft as the mair motor (constant output regulation), or can be coupled to ar induction machine and form a regulating set (constant torque regulation). This type of drive more truly belongs to the category of commutator machines than the Kramer system and, although a good deal has been said in a former chapter concerning cascaded sets, it is proposed to study the Scherbius system in some detail.

The main motor is started up in the usual manner with starting resistances, and the speed is adjusted without loss by varying the excitation of the exciter with a regulating resistance. The slip frequency, in practice, cannot be much higher than 15 cycles per second. This implies that with main motors which are supplied with 50-cycle current a maximum speed range of only 30 per cent. is obtainable, which is often insufficient to meet the requirements of rolling mills. This led to an investigation into the possibilities of super-synchronous running for the main motor (Fig. 154). By making use of speeds greater than synchronous speeds not only is the slip frequency diminished almost by half with the speed range remaining the same but also the capacity of the commutating machine and the adjoining induction machine can also be increased in the same proportion. The transition to super-synchronous running is effected in the Brown-Boveri system, by a small frequency converter which is mounted directly on the shaft of the main motor, or driven through gearing, the ratio of which depends on the number of poles of the two machines. The frequency converter influences the excitation of the exciter which supplies part of the excitation for the Scherbius machine, the remainder being taken directly from the rotor circuit. The phase and magnitude of the pressure generated in the exciter by the frequency converter are such that the excitation field of the Scherbius machine gives rise to the required current in the rotor circuit of the main motor, so that, if the latter motor reaches synchronous speed when loaded, watt current as well as wattless current flows in its rotor. Both below and above synchronous speed, the influence of the frequency converter on the excitation of the Scherbius machine gradually vanishes almost entirely a

the slip increases ; the excitation is then produced by the slip pressure of the main motor alone.

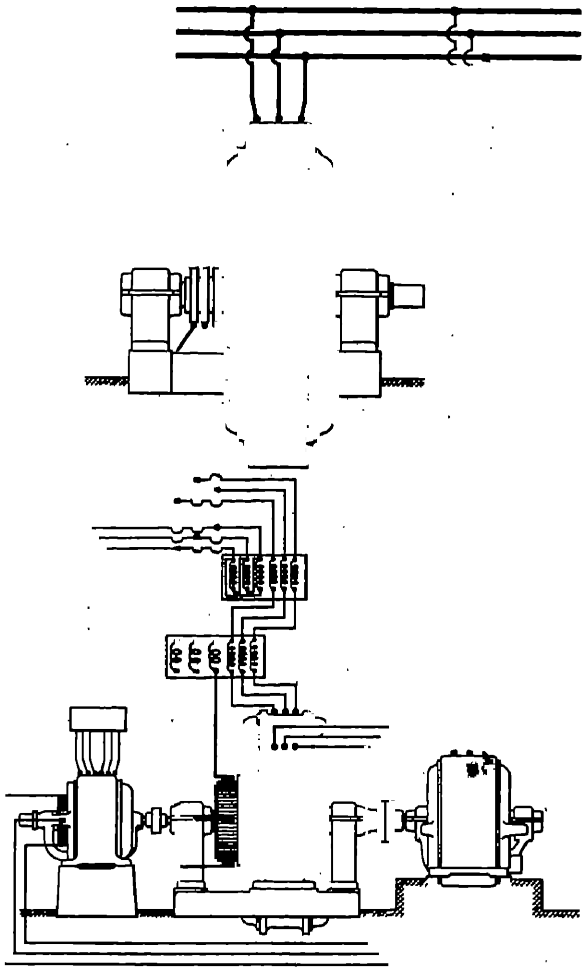


FIG. 153.—Diagram of a three-phase rolling-mill motor with Scherbius regulation for sub-synchronous speeds (Brown-Boveri) consisting of :—

Main rolling-mill motor. Induction machine.
Scherbius machine. Compounding transformer.
Exciter. Compensating transformer.
Regulating resistance.

With this system of regulation it is usually possible for the rotor of the main motor to carry the magnetising current

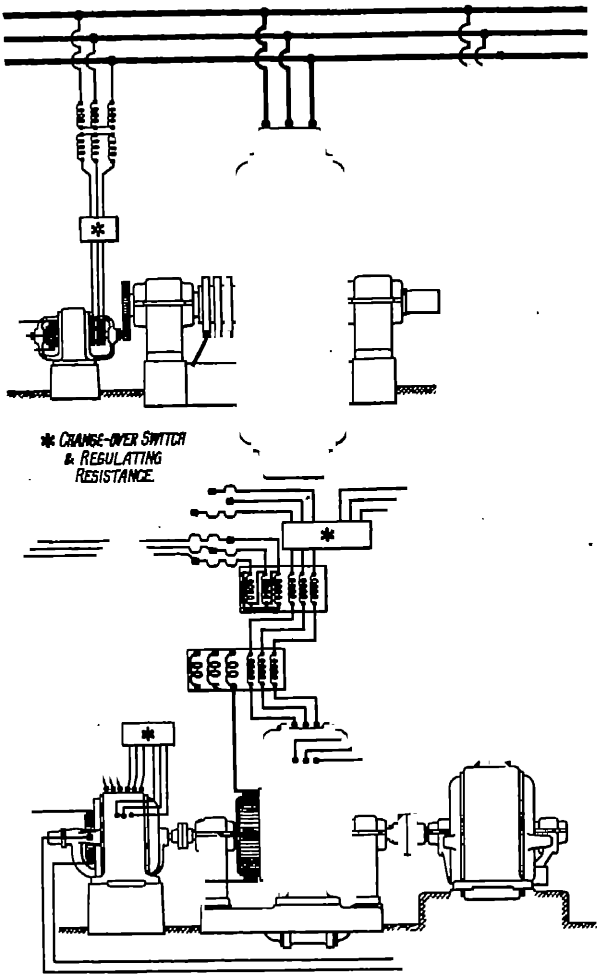


FIG. 154.—Diagram of a three-phase rolling-mill motor with Scherbius regulation for sub- and super-synchronous speeds consisting of:—

Main rolling-mill motor.
Scherbius machine.
Exciter.
Induction machine.
Compounding transformer.
Compensating transformer.
Regulating resistances and change-over switch.
Regulating resistances and change-over switch.
Frequency converter.
Regulating resistance and change-over switch.
Auxiliary transformer.

throughout the speed range and at all loads, so that the stator of this machine only takes watt current off the system, or, if necessary, wattless current to compensate for the magnetising current of the induction machine belonging to the regulating set. Consequently, the entire plant operates both at full-load and at fractional loads with a power factor equal to unity, or very nearly so. If a flywheel is employed, it is also possible to compound the commutator machine—that is, when the load increases, to produce an additional speed drop from no-load to full-load. Adjustment of the compounding to meet different operating conditions complicates the plant, and on this account is not ordinarily carried out.

Compounding is effected by means of a special transformer, the primary side of which receives the rotor current of the main motor, and the secondary influences the excitation of the Scherbius machine, thereby altering the field of the latter as well as the speed of the main motor.

The advantages of regulating both below and above synchronism are the following :—

(1) A better efficiency throughout the speed range.

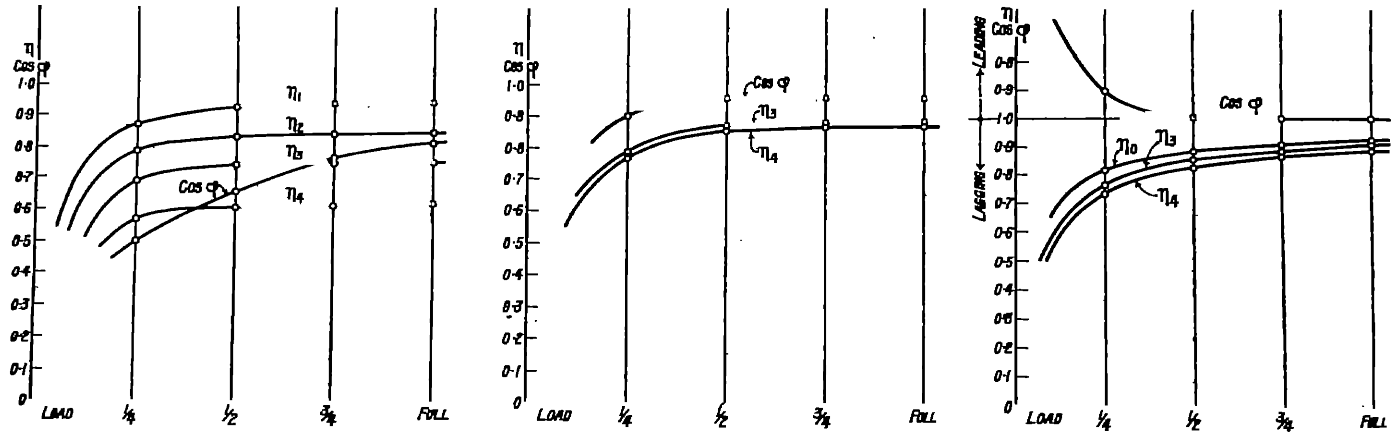
(2) Possibility of operating the rolling mill for a considerable part of the time with the main motor alone, since synchronous speed is in the middle of the speed range, this being the speed most common in rolling mills.

(3) If the speed of an existing rolling mill has to be raised this can be achieved by Scherbius regulation for super-synchronous speeds, almost without stoppage, whereas the installation of a new main motor necessitates costly reconstruction, together with a much longer interruption of the working.

(4) The regulating set is perfectly stable throughout the speed range.

(5) The power factor of the main motor can be raised to unity or even become leading in the entire speed range, and at all loads.

After this rapid survey of the Scherbius system, let us examine it a little more carefully, or, rather, let us consider the true cascaded induction-commutator motor which constitutes its fundamental principle.



(a) (b) (c)

FIG. 155.—Efficiency and power factor (cos ϕ) of three-phase rolling-mill motors, 2200 kw., 125 r.p.m., 5500 V., 50 cycles, with the following modes of speed regulation :—

(a) *With Rotor Resistances.*

η_1 = efficiency without additional resistances.

η_2 = efficiency at 112 r.p.m.

η_3 = efficiency at 100 r.p.m.

η_4 = efficiency at 80 r.p.m.

(b) *Kramer Regulation.*

η_3 = efficiency at 100 r.p.m.

η_4 = efficiency at 80 r.p.m.

(c) *Scherbius Regulation.*

η_0 = efficiency at synchronous speed, 94 r.p.m.

η_3 = efficiency at super-synchronous speed, 106 r.p.m.

η_4 = efficiency at sub-synchronous speed, 75 r.p.m.

Figs. 156, 157, and 158 show the various forms the arrangement may take, either the commutator motor and the induction

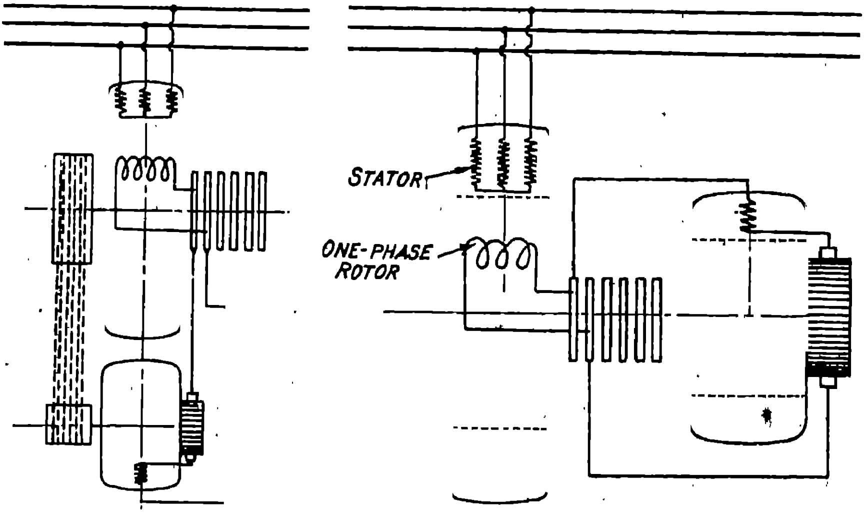


FIG. 156.—Induction motor and commutator motor coupled on the same shaft and cascaded.

FIG. 157.—Induction motor and commutator motor coupled by chain drive and cascaded.

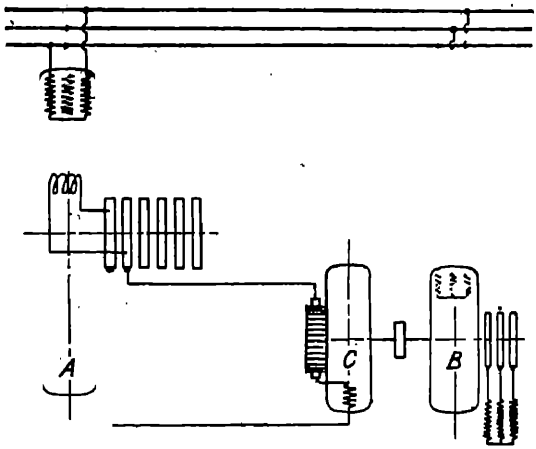


FIG. 158.—Commutator machine driving auxiliary induction generator, and cascaded with induction motor.

motor are coupled to the same shaft, or a chain drive may be used as in Fig. 157, or the commutator machine can drive an induction generator or alternator as shown in Fig. 158.

The set shown in Fig. 159, by Jeumont (Nord), is rated 1500 h.p. with provision for 100 per cent. overload. Efficiency at full load is 92·5 per cent., while the power factor is between 0·95 and unity: the set runs at a normal speed of 470 r.p.m.

Fig. 160 shows a 1600 h.p. set, wound for 5500 volts, and running at a speed of 250 r.p.m. The slip may be varied from 2 to 12 per cent. Motors of this type have been built by the Jeumont works for 3500 and even 5000 h.p.

Whichever of the three arrangements is used, the electrical characteristics are identical, and it is with these we are chiefly concerned.

Let us examine the conditions under which the speed will vary as the load increases. The rotor current when the motor is running at normal speed, will traverse the stator and the rotor of the commutator motor and produce two rotating fields, one arising from the stator, the other from the rotor. (We are dealing here with the case of an induction motor in cascade with a series commutator motor, as distinct from any other system (see Fig. 161). If the brushes are set in such a way that the two rotating fields are in opposition to one another and mutually counteract each other, the resultant rotating field will be zero. In these conditions, no E.M.F. will arise at the commutator motor terminals, and this machine will act merely as an ohmic resistance. Since the ohmic resistance is a small one, the main induction motor will run to all intents and purposes as though the rotor were short-circuited, and the

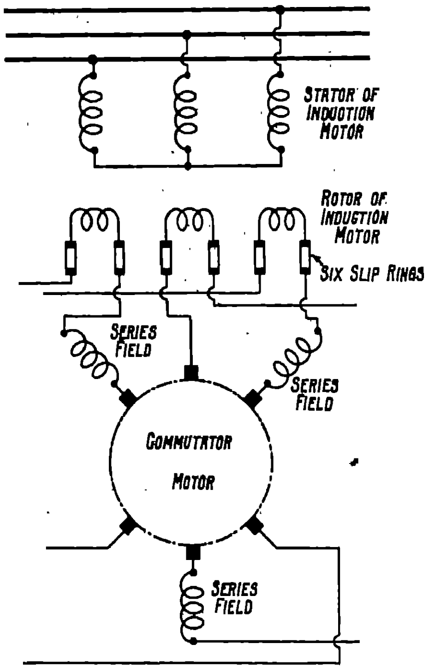


FIG. 161.—Diagram of connections of simple cascaded set.

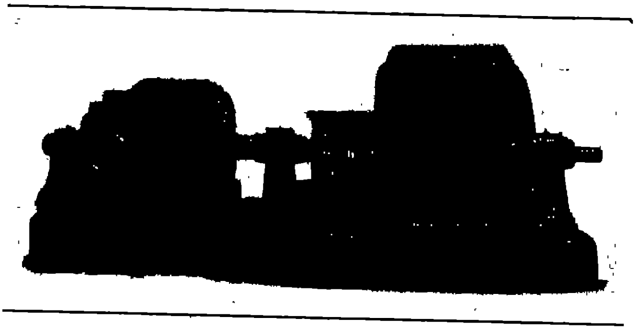


FIG. 159.—1500 h.p. cascaded set by the Forges et Ateliers de Constructions Electriques de Jeumont (Nord), with provision for 100 per cent. overload. Efficiency at full load, 92·5 per cent., and power factor between 0·95 and unity. Normal speed, 470 r.p.m.

[*To face page* 254.

characteristic will be almost horizontal (Fig. 162). We already know that a characteristic of this form is unsuitable for use with a flywheel, since it does not fulfil the primary condition necessary for efficient operation, that is, the provision of an appreciable speed-drop between full-load and no-load. But the characteristic may be easily modified as follows, and this modification, which can obviously be carried out to a lesser or greater extent, fulfils a second fundamental condition, that of being able to adjust the speed-drop. It does so, moreover, without imparing either the efficiency or the power factor.

If we shift the brushes on the commutator in such a way that the two rotating fields are at an angle α (Fig. 163), the resultant will be different from zero, and an electromotive force

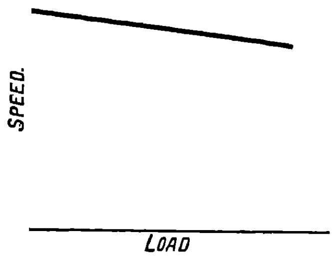


FIG. 162.—Characteristic of induction motor with rotor practically short-circuited.

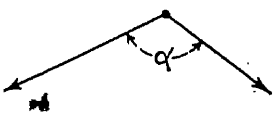


FIG. 163.—Rotating fields diagram with resultant different from zero.

will arise at the commutator motor terminals. This E.M.F. will be applied to the induction motor slip-rings, and will alter the speed of the main motor. If the commutator motor is allowed to run as a motor, the speed of the main induction motor will tend to drop. If, on the other hand, the commutator motor is driven against its own torque, the main motor rotor will receive a certain amount of energy which will add itself to that which it receives from its own stator.

Clearly, then, by this means the induction motor can be made to run at super-synchronous speeds just as efficiently as would be the case for the special Scherbius method previously described, with all the advantages already mentioned. In order to lower the speed of the induction motor, it is only necessary

to shift the brushes to a position such that the E.M.F. produced is of suitable value.

In this case, the commutator motor can either supply energy in the form of torque on the main shaft, or if it is coupled to a separate generator, restore electrical energy to the mains. However, when the main induction motor is running at no-load, its rotor current will, of course, be very low, the flux created by this current in the commutator motor will also be low, and the consequent E.M.F. almost negligible; therefore, at no-load, the induction motor will tend towards synchronism, whereas under load it will slow down the more, the more the brushes are shifted from the position for field-opposition. Thus any characteristic between AB and AC (Fig. 164) can be obtained—which is a very valuable condition for rolling-mill drives—since it allows more or less energy to be taken from the fly-wheel with varying values of the peaks.

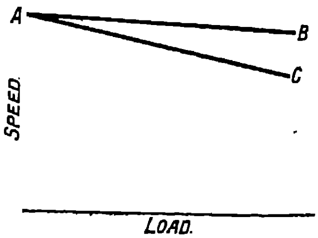


FIG. 164.—Various characteristics between limits, such as AB, AC, may be obtained with cascaded sets.

The first two conditions which a motor characteristic must fulfil for rolling-mill work are therefore satisfied. There remains a third condition, viz. that the speed at no-load should itself be adjustable, that is, that it should be possible to use several ranges of speed, for each of which the first two conditions apply. The cascaded set equally fulfils this third condition.

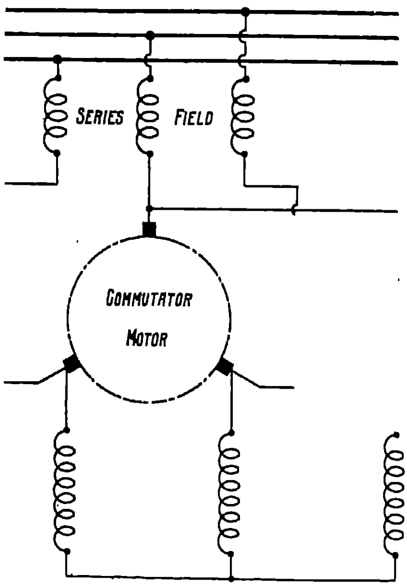


FIG. 165.—Insertion of reactances between the brushes of commutator machine in order to modify the characteristics.

We have already seen that the mechanical characteristics of the series three-phase motor can be considerably modified by inserting a reactance between the brushes (Fig. 165). Instead of running away at no-load, the speed is limited to a certain definite value (pseudo-synchronism) which depends on the value of the reactance, and will be high if the reactance is high and low if the reactance is low—the value of the pseudo-synchronous speed, however, always remaining greater than the synchronous speed—that is, than the speed of the stator rotating field. When nearing this pseudo-synchronous speed the commutator motor rotor current tends towards zero. The machine is fitted with a variable reactance S (Fig. 166), by altering which the speed of the main motor may also be altered (one phase only is shown in the diagram for clarity). As an example of this method, a set built by the Jeumont Company has the following characteristics: The synchronous speed of the induction motor is 150 r.p.m.; that of the commutator motor, 100 r.p.m. The speed of the combination can be varied from 108 to 150 r.p.m. by adjustment of the reactance.

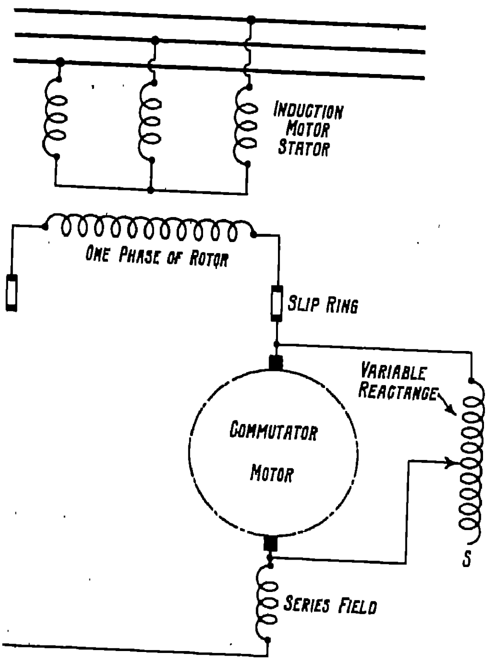


FIG. 166.—Cascaded machine with variable reactance.

The reactance can take the form of a three-phase multiple tapping coil wound on an iron core, or it may be constituted by an induction regulator with a movable rotor. The speed can, of course, be adjusted while the machine is running, and will not alter the value of the speed-drop; the angle BAC (Fig. 167)

merely shifts bodily to some such position as B′A′C′. The speed-drop may therefore be adjusted for any range of speeds.

These various characteristics can, of course, be equally well obtained whether the motor is mechanically coupled to the main induction motor, or whether it is used to drive a generator and thus restore energy to the mains.

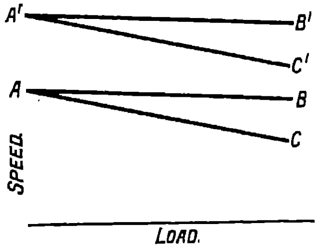


FIG. 167.—Modification of no-load speed by means of a reactance.

Rating of Commutator Machine.—The power of the three-phase commutator motor depends on the amount of slip energy that has to be recuperated from the main induction motor, and this depends on the extent of speed variation requirements. Let us consider the case of a 1000 h.p. induction motor with a speed at synchronism of 500 r.p.m. Couple this motor to a commutator machine such that the slip will be 10 per cent. on load—that is, a speed-drop of 500 to 450 r.p.m. (B, in Fig. 168). Under such conditions the power absorbed by the commutator machine will be 10 per cent. of 1000 h.p.—that is, 100 h.p.

Let us now alter the no-load speed of the induction motor to 300 r.p.m., so as to obtain characteristic CD (Fig. 168). If we maintain a speed-drop of 450 r.p.m., point D will be the point of operation on load. The energy supplied by the induction motor rotor will now be 50 per cent. of the power (since the speed is one-half synchronism). The commutator motor should therefore in this case be rated for 500 h.p.

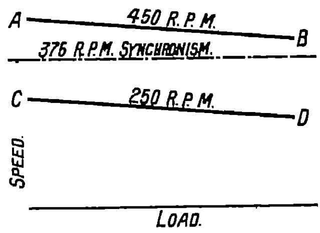


FIG. 168.—Characteristic curves of cascaded set, illustrating the question of proper rating of commutator machines.

In order to decrease the size of the commutator machine, we may choose a different main induction motor, with a synchronous speed of 375 r.p.m., for instance, and run above and below synchronism. The size of

the commutator machine will be considerably decreased because, at 250 r.p.m., it will now only have to deal with

$$\frac{375 - 250}{375} \times 1000 = 333 \text{ h.p.}$$

A further advantage of this method is that, should a breakdown occur to the commutator machine, it will be easy to disconnect it both electrically and mechanically from the main induction motor, and to use the latter alone. The speed at no-load will then be 375 r.p.m. In the former case the speed of the induction motor alone would have been 500 r.p.m., which is well above the average value suitable for rolling-mill work. In such an emergency the speed-drop would be obtained by inserting a constant resistance in the rotor circuit.

Power and Torque of Cascaded Set.—There is a considerable difference, as regards considerations of power and torque, between the case where the commutator machine is mechanically coupled to the induction motor and the case where it drives an auxiliary generator.

In the first case, the torque of the commutator motor and that of the induction motor add to one another, and their sum is applied to the mill. *The normal output of the set is constant*, whatever the speed may be. Hence, at low speeds the torque will be higher than at high speeds. This is a distinct advantage, inasmuch as flywheels possess a kinetic energy that is proportional to the square of the speed, and at low speeds have to be assisted by a higher motor torque. In the second case it is the normal torque that is constant at all speeds. The output will be proportional to the speed, and this fits in with certain requirements of the rolling-mill industry.

Characteristic Modifications.—Since all characteristics comprised within the angle BAC can be obtained by means of brush-shifting, it is obviously possible to start with a characteristic such as AB, for instance, and at a certain given value of the load automatically shift the brushes so as to come down to characteristic AC. A curve such as DEF will be obtained (Fig. 169), similar to the ideal form shown in Fig. 170. The automatic shifting of the brushes may be obtained by means of a regulator set to operate for a predetermined value of the main

current. EF can then be so chosen as to start the motor slipping for any given load. The advantages of such a system will be readily appreciated. The energy stored up in the fly-wheel can be called upon at any required moment, for instance, just as the main current reaches a limit value.

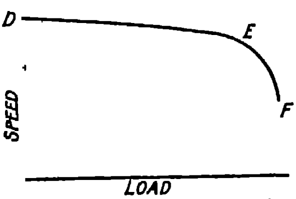


FIG. 169.—Curve obtained with automatic brush-shifting on cascaded set, approximating ideal curve shown in Fig. 170.

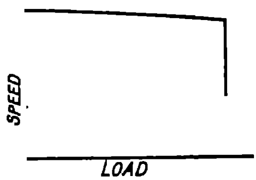


FIG. 170.—Ideal characteristic curve for rolling-mill drive (see Fig. 169).

Power Factor.—The three-phase commutator motor, running above synchronism, has a leading power factor. In the great majority of cascaded sets the commutator machine is actually running above its own synchronous speed, so that the induction motor wattless current is fully compensated (see Chapter V.). The set is so designed as to attain unity value for the power factor within wide limits of load variation. The results of this are :—

(1) Very reduced Joule losses in the transmission lines and alternators.

(2) An increased load capacity for both alternators and lines.

It would, of course, be possible so to design the set that the power factor should be leading within the limits of operation, thus compensating the wattless components of other existing induction motors. As a general rule, however, this method of operation is not commendable. Rolling-mill motors run at a relatively low speed, and consequently, in order to obtain a constantly leading power factor, the size and cost of the commutator machine would be such as to counteract any advantage in all cases where only a small number of unimportant induction motors are in use.

In such cases, it is preferable to compensate the other in-

duction motors singly, or as a group according to the methods described in Chapter V., when a fast-running motor may be chosen that will be economical.

The beneficial effect of unity power factor on the power station can best be shown by a concrete example, and will, of course, be the greater the greater the power of the cascaded set as compared to the total output of the power station.

Take, for example, a rolling mill utilising 1000 kw., with an average power factor of 0·6. The addition of a cascaded set, absorbing 1000 kw. with unity power factor, will raise the average power factor to 0·83, that is, the necessary current for providing the 2000 kw. will only be 1·44 times what it was for 1000 kw., or less than half as much again for double the power. In other words, the power station will supply, per kilowatt, a current equal to 0·72 times what it was at first. Line and alternator Joule losses for an equivalent number of kilowatts will be decreased by 48 per cent.

Braking.—If, in a cascaded set, the two motors are mechanically coupled, braking is very easily achieved. The brushes on the commutator machine may be so shifted as to cause it to act as a generator, the power being absorbed in suitable resistances.

Control and Operation.—Fig. 171 gives the simplified connections of a cascaded set. To start up, the following operations are necessary :—

(1) The high-tension circuit breaker T is closed.

(2) Switch D is closed, inserting a starting resistance in the induction motor rotor circuit.

(3) As soon as the motor reaches a certain speed the change-over switch O is put into the running position N. D is then opened, and the commutator machine thus cascaded. By adjusting the reactance L, any desired speed may be hen obtained (Jeumont).

For stopping and braking, the sequence of operations is as follows :—

(1) Change-over switch O is put into position F.

(2) The brushes are shifted back so that the motor runs as a generator, and feeds current through the resistances AB. While this is going on, the induction motor stator is still being

fed from the mains. The voltage between slip-rings allows a low excitation current to flow through the resistance in circuit KGFEHOF*r*NL, and thus the commutator machine is started up as a generator.

(3) T is then opened.

The starting resistances CB, and the braking resistances AB, are in practice composed of a number of steps, usually two for starting and four for braking.

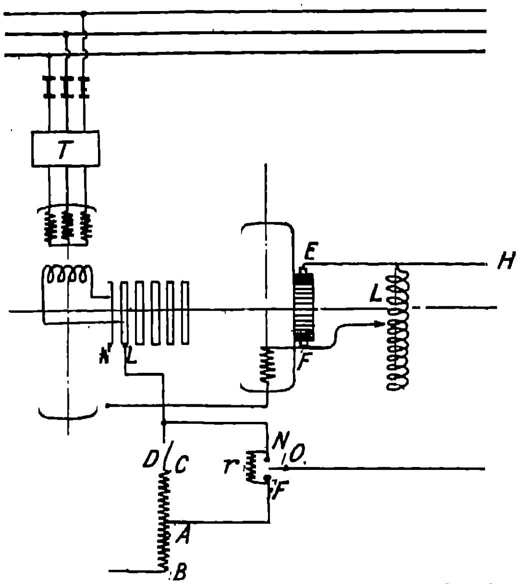


FIG. 171.—Simplified connection of cascaded set showing method of control (Jeumont).

In the case of an independent commutator motor generator set, starting is accomplished as follows (Fig. 172):—

(1) The auxiliary induction motor B is started up by closing T_2 and short-circuiting R gradually.

(2) The main motor A is started by closing T_1 and D.

(3) The sets are cascaded by closing E and opening D.

Stopping and braking are done by opening T_1 and E. The stator of the main motor A is then fed with direct current by closing switch F. The rotor circuit is connected to resistances by closing D. By increasing the value of the direct current by means of *r*, braking is realised.

As will be seen, these methods are very simple, and may, moreover, be mechanically or electrically interlocked so as to be practically fool-proof. The advantages of the cascaded set may be summed up as follows :—

Advantages of Cascaded Set.—

(1) Recuperation of rotor slip energy.

(2) Slip is obtained without any loss in resistances.

(3) Adjustment of slip to suit flywheel and operating conditions.

(4) Unity power factor within wide limits of speed regulation.

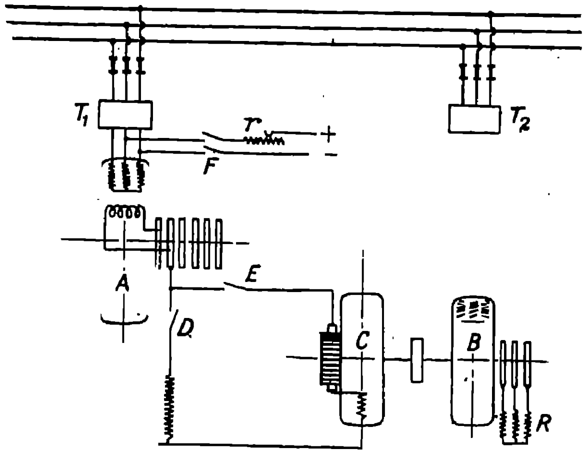


FIG. 172.—Simplified connections of cascaded set where commutator machine is driving auxiliary generator, showing method of control (Jeumont).

(5) Voltage-drop in transformers and alternators considerably reduced.

(6) Motor overload limited by natural characteristic.

(7) Variation of no-load speed possible without impairing efficiency or power factor.

(8) The commutator motor torque adds itself to the main motor torque when both motors are mechanically coupled.

(9) Characteristics easily modified when necessary.

(10) Braking easily possible.

(11) Possibility of operation above and below synchronism, and using synchronous speed as an average speed.

(12) Simplicity and ease of handling.

(13) Great robustness.

The subject of reversing rolling mills has not been approached in this chapter. In the present state of development it would seem that specially designed direct-current motors are alone suitable for this type of drive. It is the author's opinion, however, that commutator motors could be adapted for use on reversible mills, but there appears to be no data available on the subject at the present moment.

There would appear also to be possibilities in the development of a form of frequency changing device whereby an auxiliary piece of apparatus supplies an auxiliary synchronous motor coupled to the main motor with power at a frequency corresponding to the speed required. Such a drive has been tried with a fair measure of success at the Scullen Works in America. The main induction motor has mounted alongside it a synchronous motor driving a frequency converter. The function of the latter machine is to change the rotor frequency of the main induction motor to a stator frequency on the synchronous motor which corresponds to the speeds at which the main motor is to run.

The motor driving the frequency converter is quite small, as it has only to supply the losses of the frequency converter, made up of friction, windage, iron, and copper losses. The advantages of this system are not very apparent. It is inherently complicated, requires a direct-current source for excitation of the synchronous motors, and seems to have little to recommend it.

When all the conditions of rolling-mill operation are considered, there can be little doubt that if such complicated and costly systems as the Ward-Leonard set are left aside, the future lies with commutator machines, either as single three-phase motors, series or compound, for the smaller mills, or cascaded with induction motors according to the methods described.

By the use of these machines the essential conditions for rolling-mill practice are fulfilled, and that, moreover, without loss of efficiency, and with unity power factor a feature, the importance of which is daily increasing and cannot be too strongly emphasised.

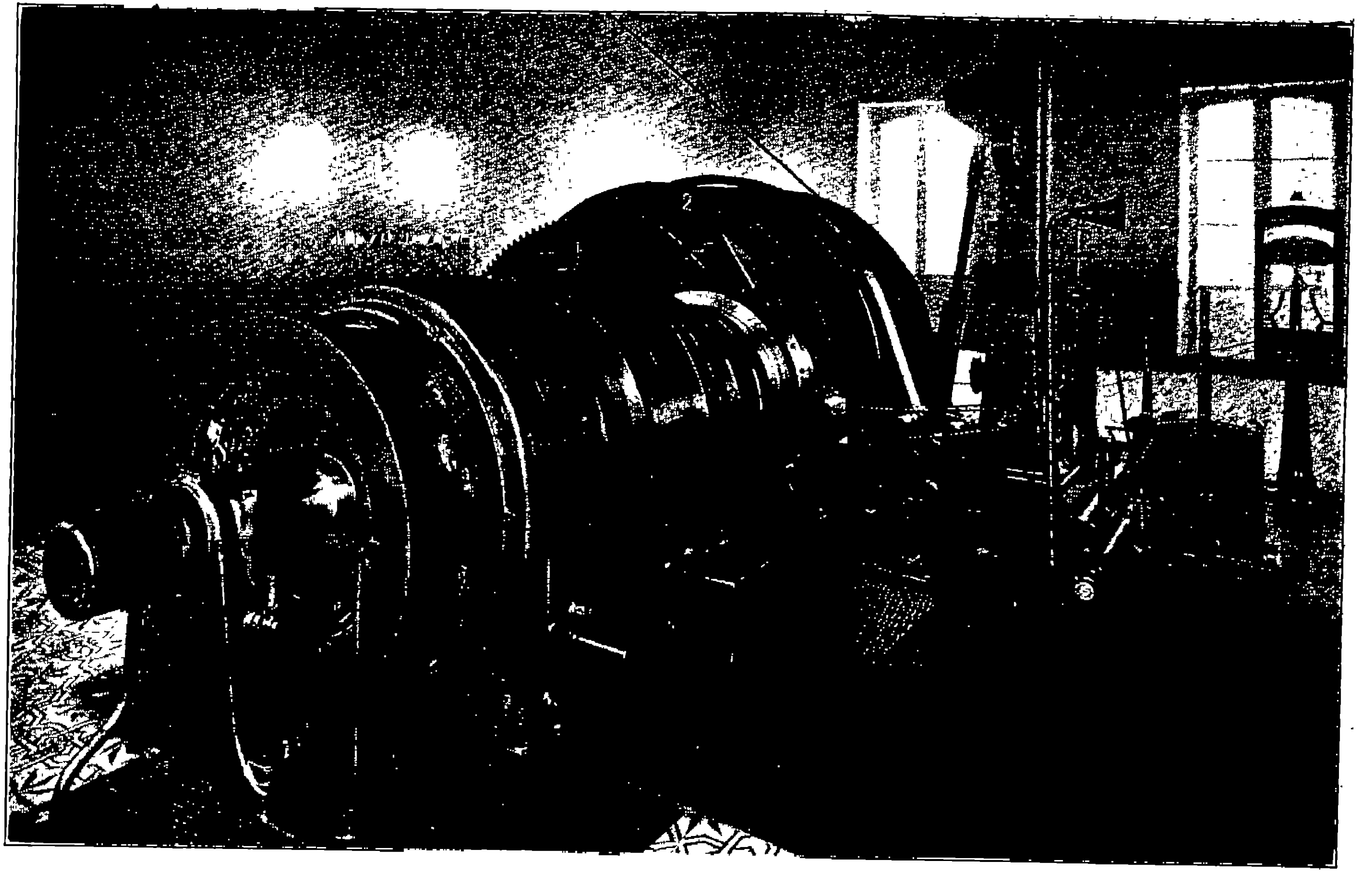


FIG. 173.—Commutator motor rated 330 h.p., driving a winding engine at the Messeix Mines, Puy-du-Dôme (Compagnie Electro-Mecanique).

[See page 265.

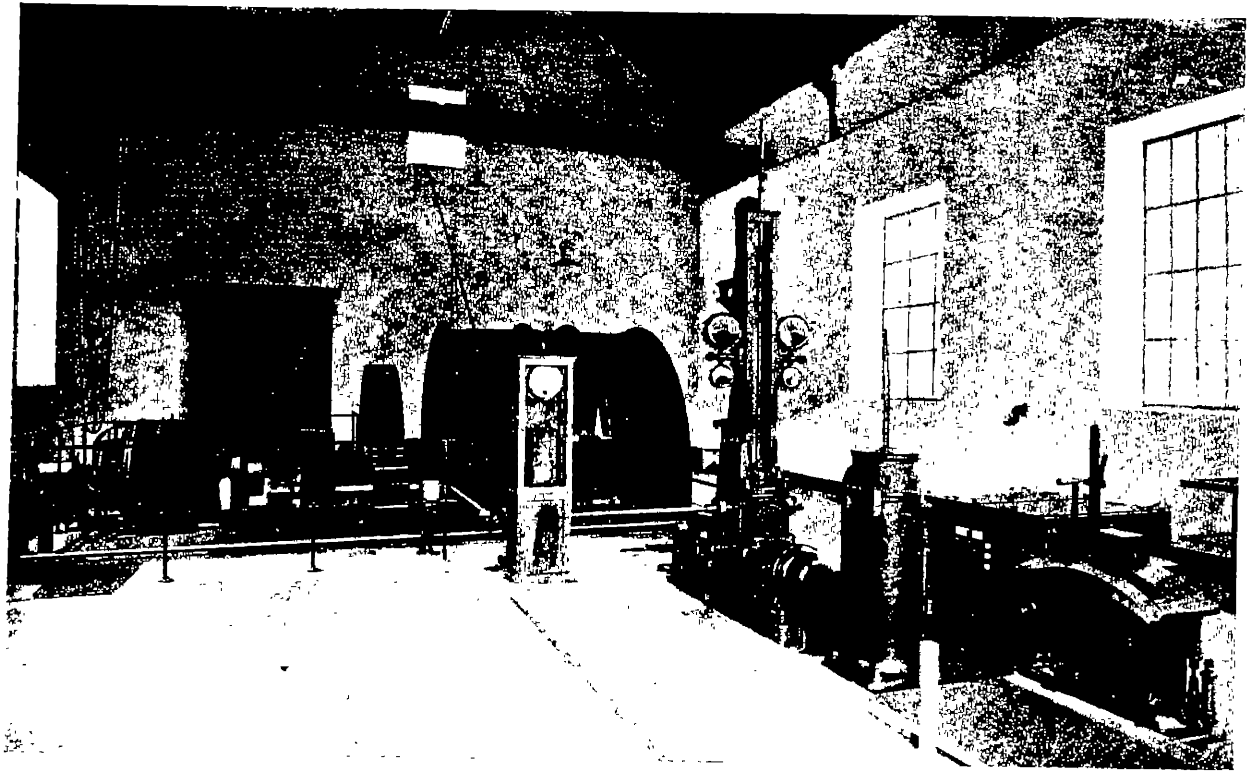


FIG. 174.—Two three-phase commutator motors, each rated 160/165 h.p., driving winding engine at the Mines de la Mure (Compagnie Electro-Mecanique).

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CHAPTER IX.

GENERAL APPLICATIONS.

ENOUGH has been said concerning the general characteristics of commutator motors to enable the prospective user to realise in what fields such a machine is applicable, and no detailed examination is necessary where a general statement will cover the facts, namely, that a commutator motor will fulfil the required conditions whenever a high power factor or accurate speed control are essential features.

There are, however, a certain number of special applications for which this type of motor is more particularly suitable, and it is the object of the present chapter to examine these briefly.

As regards the larger motors, apart from traction and rolling-mill drives, there would seem to be a considerable field for their development in collieries. During the past few years, both surface and underground machinery has been increasingly electrified in collieries both in England and abroad, and the growing importance of electrical drives is well worthy of close examination. Only a comparatively small number of winding-engines have as yet been fitted with a drive of this type, but there seems to be no reason why these motors should not be more extensively used in this respect. The photograph reproduced in Fig. 173 shows a winder at the Messeix Mines, Puy-du-Dôme, driven by a 330 h.p. three-phase commutator motor built by the Compagnie Electro-Mecanique. It will be seen that the motor is provided with a double commutator, as is often the case with the larger motors. The winder shown in Fig. 174, at the Mines de la Mure (Isere), is driven by two three-phase commutator motors, each rated 110/165 h.p., 500 volts, 50 cycles, 750 r.p.m., geared to the ratio 750/21·8.

The great popularity of the Ward-Leonard system, where accurate speed regulation is required, has considerably hindered

the application of the A.C. commutator motor to the drive of winders, and, in spite of its remarkable qualities, there does not seem to be any immediate prospect of its development in this field.

For fan drives, on the other hand, the commutator motor is being widely used, and has proved reliable, efficient, and highly economical. Fig. 175 shows a 330/160 h.p., 3000 volts, 50 cycles, 879/693 r.p.m. motor, by the Ateliers de Jeumont, driving a fan at the Mines de la Clarence, Calonne Riquart, Pas de Calais. As regards English installations, the photograph reproduced in Fig. 176 shows a fan at Peckfield Colliery, Yorkshire, owned by the Micklefield Coal and Lime Co., Ltd., which is provided with a double drive. A commutator motor by the A.E.C., rated 360 h.p., 2000 volts, 50 cycles, has a speed variable between 260 and 600 r.p.m., an important advantage during certain periods. Twenty-four different speeds can be obtained; after the sixth speed, the power factor is unity up to full speed. A Mather and Platt synchronous motor has now been added for normal running.

A.C. commutator motors have been very extensively used on the Continent for such applications as fans or compressors, for powers up to 850 h.p. and speed ranging from 100 to 1000 r.p.m. or more.

There are no qualities inherent to such control systems as the Ward-Leonard, which cannot be precisely reproduced by systems of the Scherbius type; the favour of the Ward-Leonard system, due to the early imperfections of A.C. control, has retarded the development of other systems, but a close examination of the claims of the A.C. systems should leave little doubt in the reader's mind as to their future.

Pumping machinery, and underground haulages should also considerably benefit from the application of A.C. commutator motors, and the author feels sure that there is a very great field for this type of machine in collieries.

Textile Industries.—The conditions which spinning machines in wool mills have to satisfy are well known to be most exacting. Following the requirements of the markets, the machine is required to spin the greatest variety in quality of wools, from coarse to fine counts, and very often soft

FIG. 175.—330 h.p., 3000-volt commutator motor driving a mine fan. Speed, 879 to 693 r.p.m. The rotor-stator transformer is shown.

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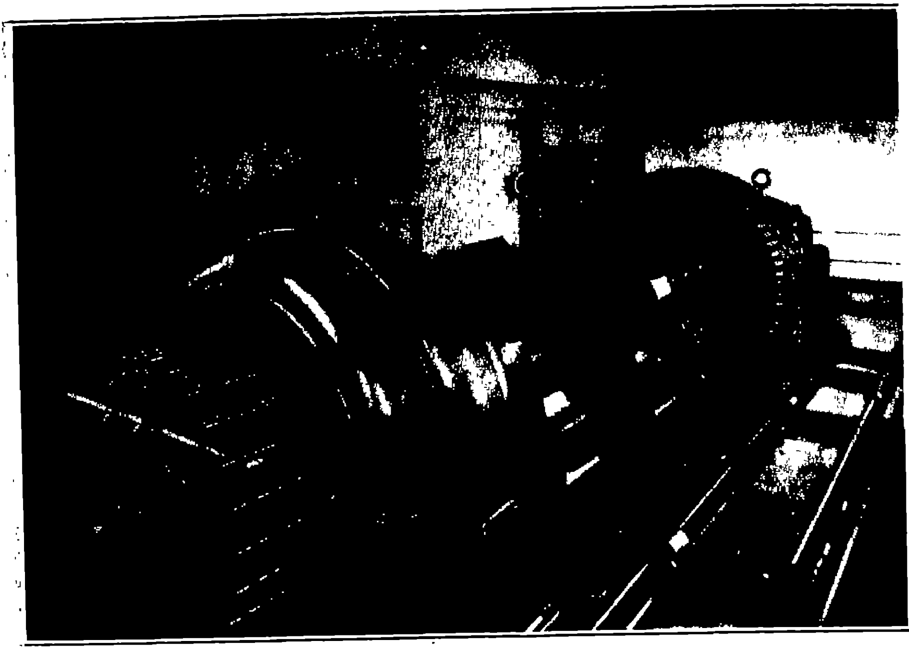

FIG. 176.—A.E.C. commutator motor driving fan at Peckfield Colliery, Yorkshire, rated 360 h.p., 2000 volts.

[See page 266.

yarns. The spinning speed, which naturally depends on the dexterity of the operator, is influenced further, according to each wool mixing, by the properties of the wool, the setting of the machine, and the humidity of the atmosphere.

Smooth starting of the spinning frame, and the possibility of varying the working speed within wide limits are essential features demanded by the spinner, and manufacturers of spinning machines, regarding the case from a purely constructional point of view, have tried to solve the problem mechanically.

To effect this, they have provided in the headstock of the spinning frame a rope gearing which is designed with the object of obtaining smooth starting of the machine. The required spinning speed is then obtained in each particular case by changing the driving pulley of the rope transmission system, which, being on the main shaft, rotates at an almost constant speed.

This system possesses obvious defects, the most important of which, from a purely practical point of view, is the inconvenience involved in readjusting the spinning speed when once it has been set. The state of affairs, however, assumes an entirely different aspect with the adoption of the individual electric drive, with speed regulation, which meets in a much simpler way, and fulfils to an ampler degree, the requirements peculiar to the spinning of wool. The motors used for the direct drive of spinning machines are either single-phase or three-phase commutator motors. The speed variation which is effected by the simple displacement of the brush-shifting lever mounted on the frame of the motor, does not affect the motor efficiency which remains constant over the entire range. This system of driving not only replaces the heavy and costly transmission belts, but also allows the complete elimination of the bulky and inefficient rope gearing. Moreover, the speed may be adjusted at any moment to obtain the most favourable working conditions.

The results obtained show that setting the speed to suit the working conditions, not only considerably increases production, but also produces a thread of superior quality ; considering the present high price of wool, the application of the variable speed electric drive, therefore, appears to be an effec-

tive road to economy. Views of two such installations are given, Fig. 177 and Fig. 178. The motors are totally enclosed and supplied with forced ventilation. Being dust-proof, and protected against accidental damage, they require little attention.

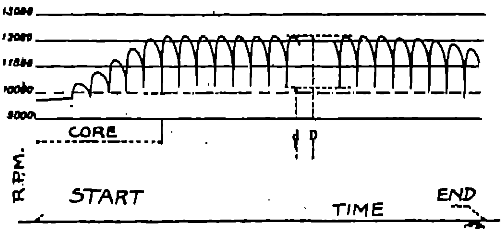

FIG. 179.—Curve showing speed regulation on continuous spinning frame provided with an automatic regulator (Compagnie Electro-Mecanique).

Spinning with a speed which varies automatically as the reel is wound has solved a very great number of difficult problems of too special a nature to describe here, but one of the outstanding advantages lies in the possibility of obtaining constant tension on the thread and hence more evenness. Moreover, the speed being always kept at an optimum value,

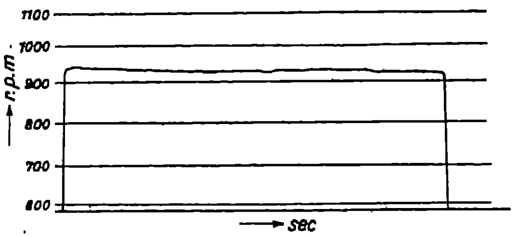

FIG. 180.—Speed of tin drum of a fine spinning frame driven by a squirrel-cage induction motor. Speed not capable of regulation. Mean speed, 930.

a better and more efficient utilisation of the loom is ensured. An increase in production of some 10 to 15 per cent. may result from this alone.

From a practical standpoint variable speed spinning is only really possible where A.C. commutator motors are used, the brush-shifting gear being directly operated by the loom. Fig. 179 shows a diagram of such a variable speed arrangement.

FIG. 177.—Individual drive of textile machinery by Brown-Boveri three-phase commutator motors.

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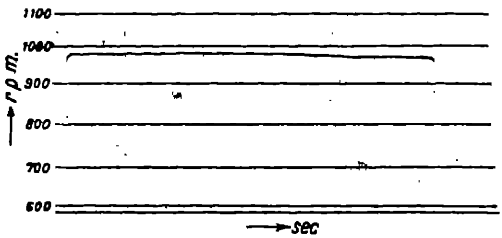
FIG. 178.—Individual drive of spinning machinery by Brown-Boveri single-phase commutator motors.

[*See page* 268.

Single or three-phase motors may be used for this purpose, speed varying from 600 to 1200 r.p.m. Such motors may, reover, be designed to rotate in either direction, a very useful nt in some forms of spinning.

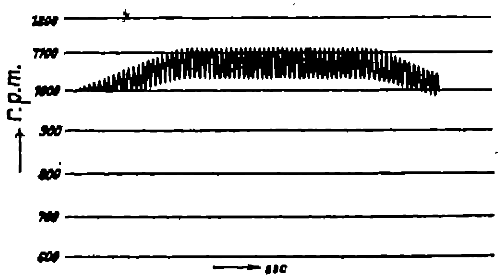
The curve in Fig. 180 shows the speed during the spinning



. 181.—Speed of tin drum of a fine spinning frame driven by a three-phase variable speed commutator motor. Hand regulator. Mean speed, 980.

cess, the spinning machine having been driven by a three-ıse squirrel-cage motor, i.e. at constant speed.

The curve in Fig. 181 shows the speed of a similar spinning chine under similar conditions, but driven by a variable ed three-phase commutator motor. In this case the adjust-



. 182.—Speed of tin drum of a fine spinning frame driven by a variable speed three-phase commutator motor. Automatic speed regulation by spinning regulator. Speed, 1040 to 1120.

nt of the highest permissible speed was effected by hand. e result is 5 per cent. increase in production over the spin-g machine driven by the squirrel-cage motor.

The curve in Fig. 182 shows the speed of the same spinning chine driven by a variable speed three-phase commutator tor in which, however, the regulation of the speed during spinning operation was automatically governed by the

spinning regulator. As compared with regulation by hand, an increase in the production of about 10 per cent., and as compared with the drive by squirrel-cage motor, an increase of about 15 per cent. was obtained.

Apart from the cotton industry, the individual electric drive of fine spinning frames by means of three-phase commutator motors has been taken up to a large extent by the wool spinning industry.

In this industry a separate motor is frequently employed on each side of the spinning machine. In this manner it is possible to spin different counts or different kinds of yarn on each side of the frame. The direction of rotation of the motors can easily be reversed, so that it is also possible to produce yarns with left-hand or right-hand twist.

Paper Industry.—The pulp and paper industry also opens a wide field for the commutator motor. The adjustable speed end of a paper-making machine is nearly always driven by a direct-current variable-speed motor, even when the primary supply available is three-phase. Smaller ranges of speed regulation are generally obtained by Ward-Leonard control, while to get more extended ranges of speed, a booster set is installed.

In printing works, electricity has simultaneously reduced the cost of operating, and made production quicker, more flexible, and more accurate. Jobbing and flat-bed presses, taking from 2 to 8 kw., are generally driven by single-phase commutator motors, the speed of which may be varied without loss. Starting, speed adjustment, stopping and braking are done from the operator's stand by simply turning a handle, which is connected to the brush rocker by suitable bevel gear. With big presses, the motor is generally a variable speed three-phase commutator motor, with an auxiliary brush-shifting motor and push-button control.

Fig. 183 shows a commutator motor with an auxiliary brush-shifting motor driving a printing press (Brown-Boveri).

A.C. commutator motors, or rather those with series characteristics are not suitable for driving paper-making machines, because their speed varies more or less as the torque changes, and the paper would not be even in weight, unless very com-

FIG. 183.—Motor-driven brush shifting gear on printing press drive (Brown-Boveri).

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FIG. 185.—View of one of the A.C. commutator motors installed at the Bowater Paper Mills (Thomson-Houston).

plicated devices were added to compensate for the variations in speed. It is in instances of this kind that motors of the shunt and compound types described in an earlier article may be successfully applied, and this affords a good example of the variety of uses to which suitably designed motors of the type may be put.

The running of a paper machine is characterised by the special requirement that the speed for which the machine is set, both as regards the absolute speed and the relative speeds between the various parts of the machine, must be kept constant within very close limits, while at the same time it must be possible to adjust this speed over a very wide range. Formerly, paper machines were, in general, driven by variable speed steam engines. The different parts of the paper machine were connected together by belt drives with conical pulleys and friction clutches so that correct variations in speed between the various sections could be arranged. During the last ten or twenty years, however, there has been a tendency to change over to electric drives, the paper machine simply being run by an electric motor instead of a steam engine and various arrangements being adopted for transmission between the various sections.

The arrangement shown in Fig. 184 is due to the British Thomson-Houston Co. Ltd., and is installed at the Bowater paper mills (see also Fig. 185).

The drawing is fairly self-explanatory. The top cone-pulley is provided with windings as shown, and any alteration in the speed, which no longer coincides with the frequency set on the variable frequency alternator will cause a relative motion and consequent shifting of the brush-gear. On the other hand, the speed of each individual drive can be altered by means of the auxiliary motor which, through a worm-screw and belt-guide, shifts the belt along the cone-pulleys.

There are a number of combinations of this kind, most of which have not, as yet, been brought up to a really satisfactory state of development, but there is an undoubted future for the commutator motor in conjunction with the paper industry. But it may be stated positively that motors of the shunt type or compound type are the only ones truly adaptable to this kind of work.

Occasionally one hears it objected that the direct use of a three-phase supply introduces the disadvantage that the absolute speed varies with the frequency of the supply. This, however, is not the case any more than it is with the D.C. system. The absolute speed of the leading driving motor can easily be kept by means of a regulator. For example, a mechanical centrifugal governor can be used for this purpose. It is

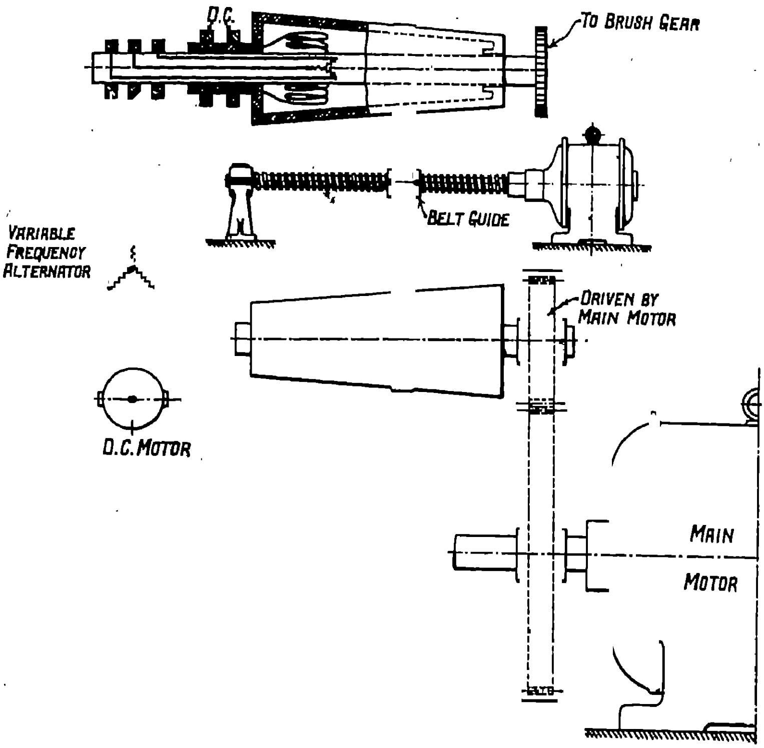

FIG. 184.—Diagram showing operation of speed regulation device at Bowater Paper Mills (Thomson-Houston).

also possible to use a tachometer generator, electrical regulator and operating motor for adjusting the brush rockers of the leading motor. Other means of similar character might also be used. There is, accordingly, no doubt that the system employing commutator motors is technically quite satisfactory. The question whether or not it will be of economic value must be investigated in each case, as the saving due to the elimination

of the primary unit may be outweighed by the more expensive motors.

It would be of no particular interest to describe in detail the number of applications to which the commutator motor can be put. An examination of its characteristics will make it quite easy for the prospective user to decide whether in the particular case under consideration such a motor should be chosen or not.

Such motors are naturally well suited for driving tools and machines, the speed of which is changing periodically or constantly, and the load conditions of which do not change, or, in cases where speed fluctuations are not a disadvantage. Their use is to be recommended in all cases where frequent starting up against a high torque is necessary.

Three-phase commutator motors, generally, may be used with advantage for driving :—

Fans, reciprocating pumps, cloth and paper printing machines, ring-spinning frames, mercerising machines, hoists, cranes, transporters, haulage gears, turn tables, rolling mills, automatic pumping installations, etc.

Recent tests taken on rotary printing presses driven by 50 h.p. equipments, showed a saving in the power bill of approximately £150 per annum over an induction motor with rotor resistance speed control. There was also a saving of about 25 per cent. in time over the induction motor, due to the rate of acceleration of the motor being practically independent of load. In the case of the induction motor, the grading of the resistances had to be suitable for all conditions of loads, and so on heavy loads the time to accelerate the press to printing speed was much greater than on light loads.

This commutator motor has also met with unqualified success in driving hydraulic pumps where a constant pressure with a varying demand is required. An accumulator works in conjunction with the pump, and its rise and fall lowers and raises the speed of the motor automatically, thus maintaining maximum storage capacity without frequent and objectionable starting and stopping of the motor.

In the field of machine tool drives, this motor has also proved its worth, particularly on large wheel lathes where it

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is desired to decrease the speed when hard parts of the tyres are being machined.

Application of Scherbius System to Pumping Sets.—Two pumping equipments with Scherbius regulation are being supplied by the British Brown-Boveri, Limited, to a new important pumping station in the Midlands.

The equipment consists of two vertical shaft 650 h.p. induction motors to run at a full-load speed of about 725 r.p.m. and to operate on a 440 volts, 25 cycles, three-phase supply. With the Scherbius regulating sets referred to below the contInous output of these motors will be increased to 710 h.p. for the same temperature rise and on overload to 780 h.p. with a temperature rise not exceeding 50° C. above that of the surrounding atmosphere.

Each motor will have its own Scherbius regulating equipment consisting of one Scherbius commutator machine coupled to a three-phase induction machine, the set to run at about 1430 r.p.m. In addition each set will have an exciting transformer together with the necessary rotor starter and switch gear for operating it. The whole plant will, in addition, comprise two three-phase transformers which are being provided to step down from 11,000 volts to 440 volts, the output of each being 1200 k.V.A. By means of the Scherbius equipments speed regulation to the extent of 13¾ per cent. is being provided for and it is expected that the following figures will be obtained:—

R.p.m.	645	685	705	725
Power absorbed by pump, b.p.h.	535	617	658	703
Overall efficiency, per cent.	87·5	88	89	89·5
P.F., leading	0·98	0·98	0·99	—
P.F., lagging	—	—	—	0·98

As has been mentioned the Scherbius system of regulation is essentially very simple both in theory and its application to practical conditions and while a great many of these sets have been supplied on the Continent this is the first time the opportunity has occurred for installing them in this country.

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